Starburst Galaxies Observed With the Hubble Space Telescope

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The contributions of the Hubble Space Telescope to our understanding of starburst galaxies are reviewed. Over the past decade, HST's imagers and spectrographs have returned high-quality data from the far-ultraviolet to the near-infrared at unprecedented spatial resolution. A representative set of HST key observations is used to address several relevant issues: Where are starbursts found? What is their stellar content? How do they evolve with time? How do the stars and the interstellar medium interact? The review concludes with a list of science highlights and a forecast for the second decade.

1. Overview

Almost exactly 10 years ago STScI hosted its annual symposium entitled *Massive Stars in Starbursts* (Leitherer et al. 1991). Those were the weeks immediately prior to HST's launch, and the conference organizers felt it appropriate to have a meeting on the subject of starbursts because HST had the potential for significant contributions. Starbursts are *compact* ($10^\circ-10^3$ pc), *young* ($\sim10^6-10^8$ yr) sites of star formation, often with high *dust* obscuration. These properties make starbursts ideal targets for HST, given its superior spatial resolution, ultraviolet (UV) sensitivity, and (later-on) infrared (IR) capabilities.

As we all know, the high hopes were not immediately fulfilled, and it was not until after the First Servicing Mission that HST lived up to the expectations. Nevertheless, it is worth noting that HST's first scientifically useful image after the launch was a WF/PC exposure of the central region of 30 Doradus in the Large Magellanic Cloud (see p. xi of Leitherer et al. 1991) — a star-formation complex which is considered the "Starburst Rosetta" by Walborn (1991).

Over the first 10 years of its life, and in particular after the installation of Costar, HST has made significant contributions to the field of starbursts which have helped address fundamental issues such as: the birthplace and environment of starbursts, the stellar content of starbursts, the temporal and spatial evolution of starburst, and the effects of starbursts on their environment. I will address these points in this review from an observational point of view, guided by the relevant HST data. Of course the selection reflects my personal perspective, and space limitations do not allow me to discuss other, similarly important material.

2. Starburst Hosts

Starbursts are a mixed bag. There is a continuum of objects between sites of massive-star formation like W51 in the Galaxy (Goldader & Wynn-Williams 1994) and the nucleus of the nearby dwarf galaxy M82 (Rieke et al. 1980). The latter is considered a prototypical starburst galaxy whereas the former is usual taken as a "normal" star-formation region. Since starbursts are selected on the basis of their high levels of ionizing and non-ionizing UV radiation (observed directly or via reprocessed recombination-line or thermal dust emission), I will use an empirical definition: Starbursts have star-formation

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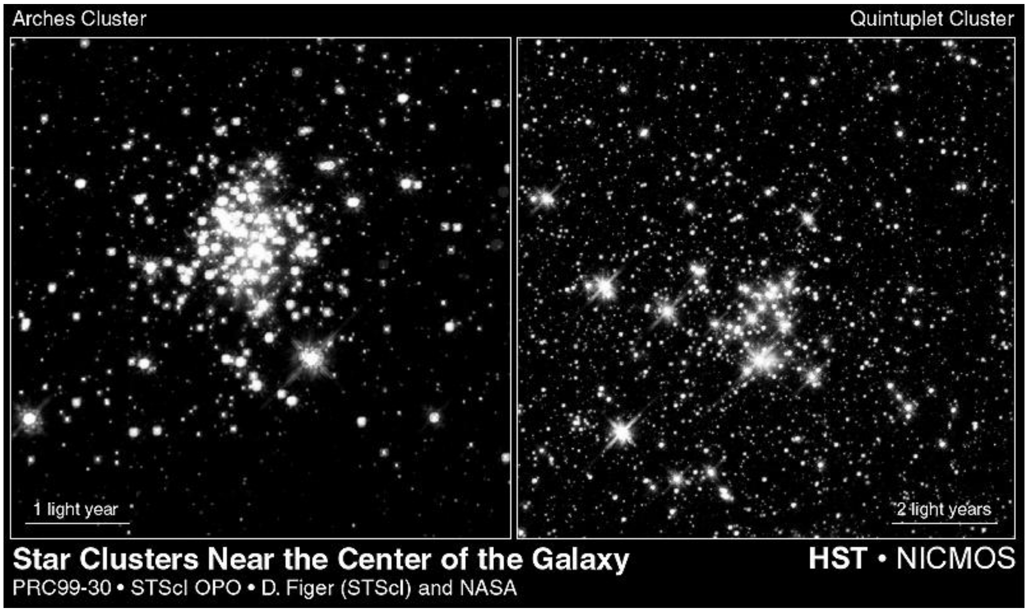

Figure 1. Composite HST NICMOS F110W, F160W, and F205W images of the Arches and Quintuplet clusters in the Galactic Center region (Figer et al. 1999).

rates high enough that a statistically significant number of stars form which produce UV radiation. Such stars have masses between 10 and 100 $M_\odot$. Therefore an equivalent definition is to require the upper mass function to be well enough populated that stochastic effects are not important. A sufficiently populated mass function leads to total starburst masses of at least about 10^5 $M_\odot$.

Following the definition of Terlevich (1997), we can extend the definition from a starburst to a starburst galaxy: In a *starburst galaxy* the entire luminosity is due to the starburst itself ($L^{\rm Burst} \approx L^{\rm Galaxy}$); if the starburst luminosity is substantial but smaller than the host galaxy luminosity ($L^{\rm Burst} < L^{\rm Galaxy}$), a *starburst region* in a galaxy is observed; if $L^{\rm Burst} << L^{\rm Galaxy}$ for any individual star forming region, the object is classified as a *star-forming galaxy*.

With these definitions, the central region of our Galaxy (Genzel & Eckart 1998) is at the low-mass (and by implication, the low-luminosity) end of the starburst scale. The region has been known for some time to be the site of massive star formation but it was HST, together with the largest ground-based telescopes, which provided the first census of the massive-star population. The Galactic Center region is of particular interest due to its proximity of 7.5 kpc, permitting a close-up view of a metal-rich, dust-shrouded small starburst. It can serve as a training ground for calibration of methods to be applied to distant, dust-obscured starburst galaxies.

The strong gravitational field in the Galactic Center is predicted to lead to a rapid evaporation of newly formed star clusters (Kim et al. 1999), consistent with the observed absence of clusters older than tens of Myr. Survival times of young star clusters are of relevance to the interpretation of the cluster luminosity function of merging galaxies where the evolutionary link between newly formed and old globular clusters has not yet been established (Zhang & Fall 1999).

Evidence for a high metallicity in the center region is overwhelming but individual studies are still discordant. The observed Galactic oxygen abundance gradient of

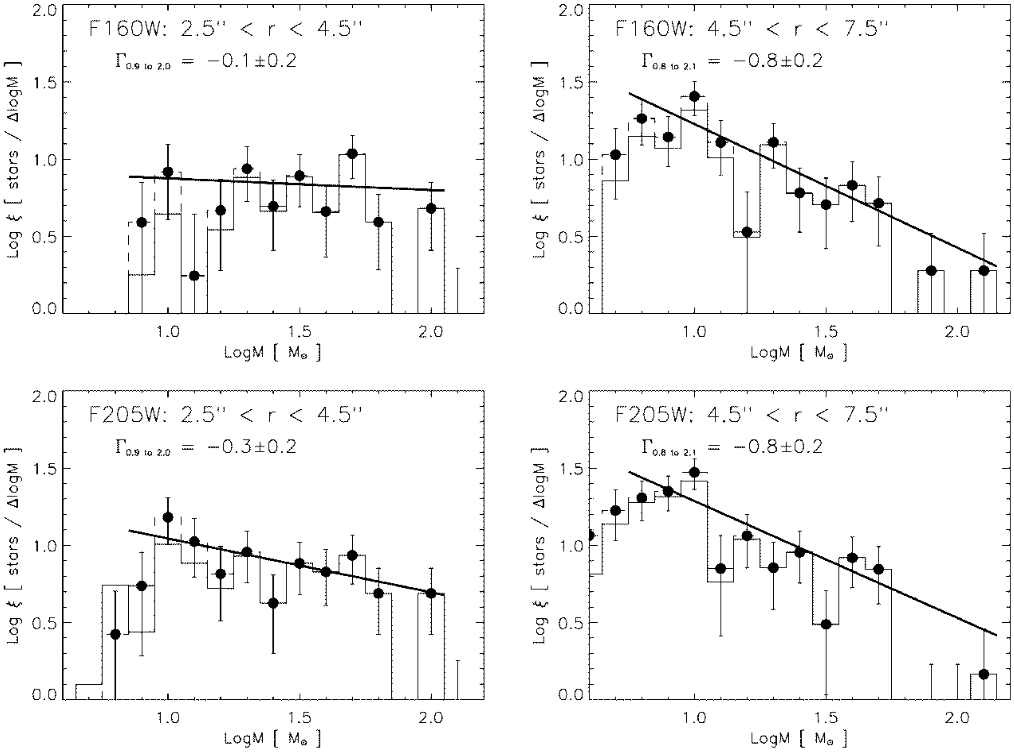

FIGURE 2. IMF of the Arches cluster derived from the F160W (top) and F205W (bottom) photometry of Fig. 1. Left: inner region; right: outer region (Figer et al. 1999).

-0.07 dex kpc^{-1} (Smartt & Rolleston 1997) suggests $Z \approx 3$ Z$_\odot$ for the Galactic Center. This agrees with an Fe abundance of about 3 Z$_\odot$ found for the luminous, hot "Pistol Star" by Najarro et al. (1999). In contrast, Ramírez et al. (2000) analyzed several red supergiants close to the Galactic Center. They found an average Fe abundance of -0.09 dex, i.e. close to the solar value. The reason for the discrepancy is not yet understood. It may indicate a real abundance spread, or just be caused by systematic errors in either one of the atmosphere analyses.

Figer et al. (1999) performed HST NICMOS near-IR imaging of the Arches and Quintuplet clusters, two very young clusters near the Galactic Center. Their composite images are reproduced in Fig. 1. Using crowded-field photometry, the luminosity function could be derived. Subsequently, evolution models allowed conversion to a mass function (Fig. 2). Figer et al. identified main-sequence stars with initial masses well below 10 M$_\odot$ and derived a slope of the initial mass function (IMF) that suggests an excess of massive stars in the cluster center relative to the periphery. The ages of the two clusters are 2 – 4 Myr.

The Galactic Center can be contrasted with Arp 220, an IR-luminous galaxy at $d =$ 77 Mpc, 10^4 times more distant than the Arches and Quintuplet clusters. At that distance, $1''$ corresponds to 400 pc. (For comparison, the smallest structures resolved in the Galactic Center by NICMOS are about 0.004 pc.) A multi-band NICMOS image taken by Scoville et al. (1998) is in Fig. 3. The image clearly resolves the twin nucleus which has resulted from a recent merger. Numerous luminous super star clusters have formed during the recent starburst episode. The total bolometric luminosity of Arp 220

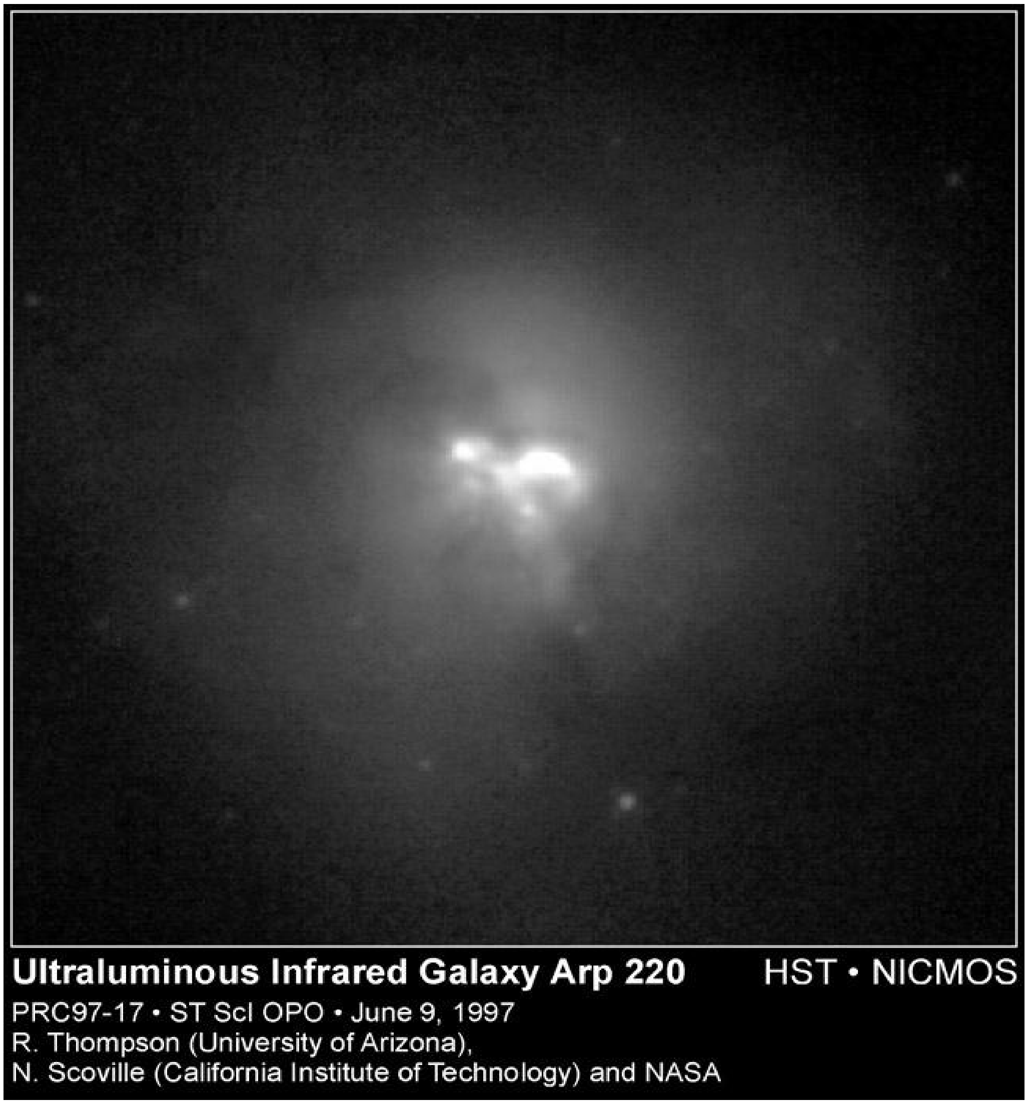

FIGURE 3. Composite HST NICMOS F110W, F160W, and F222M image of Arp 220. Field size is 19″ or 7.5 kpc (Scoville et al. 1998).

can be accounted for by star formation alone (Smith et al. 1998). This leaves open the significance of an active galactic nucleus (AGN), which may be contributing as well.

The relative importance of the starburst versus the AGN in Arp 220 is not clear. It is one of HST's major scientific achievements to demonstrate that at least in some galaxies hosting an AGN a central starburst can be dominant in the UV to near-IR energy output and can be significant bolometrically as well. The presence of starbursts in active galaxies was suggested before (e.g., Terlevich 1992) but observational proof has remained elusive: young massive stars have few strong spectral features in the optical and near-IR so that their presence is easily hidden by a strong non-stellar continuum and by emission lines. The situation changes in the UV, where hot stars have unique, broad Si IV $\lambda1400$ and C IV $\lambda1550$ features. HST's UV sensitivity, combined with its spatial and spectral resolution allowed the detection of *undiluted* stellar lines, and therefore proof that stars

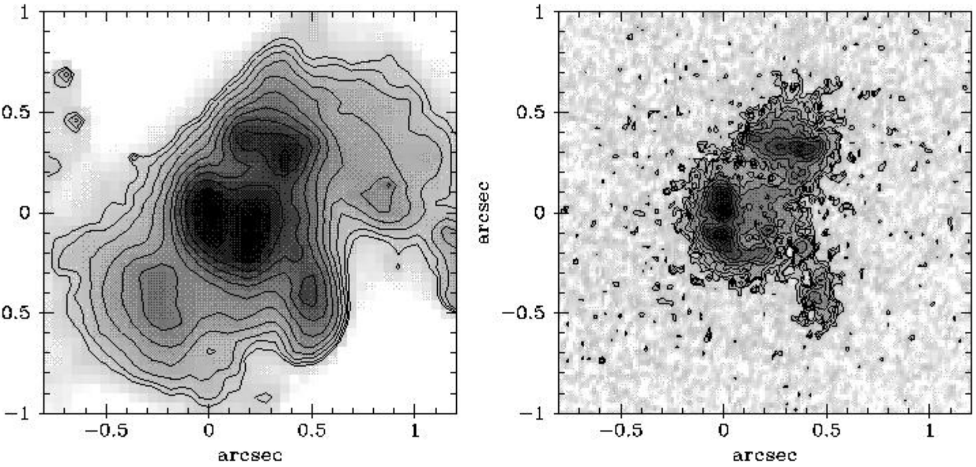

Figure 4. Central 2″ × 2″ (620 × 620 pc) of NGC 7130 in optical (left) and UV (right) light (González Delgado et al. 1998).

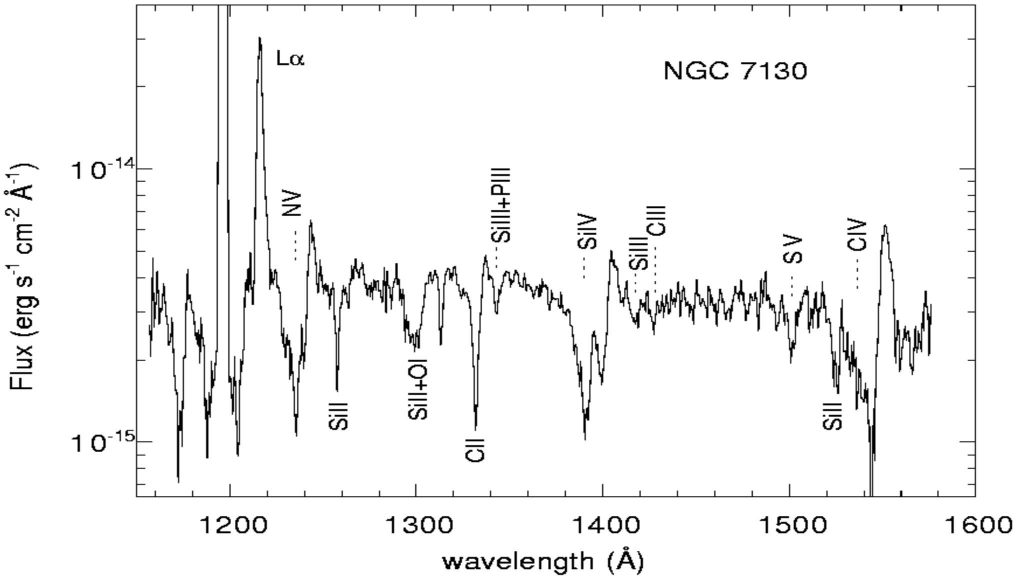

Figure 5. UV spectrum of the nucleus of NGC 7130 obtained through the 1.7″ × 1.7″ square aperture of the GHRS on HST. The strongest features are the stellar-wind lines of Si IV λ1400and C IV λ1550 (González Delgado et al. 1998).

dominate the continuum in some active galaxies (González Delgado et al. 1998; Maoz et al. 1998).

HST WFPC2 and FOC 2200 Å imaging of a sample of UV-bright Seyfert2 galaxies was done by González Delgado et al. (1998). Their images of NGC 7130 are shown in Fig. 4. The nucleus, which was previously thought to be point-like, displays a complex morphology, suggestive of a circumnuclear starburst ring. The true nature of the emitted light becomes even clearer from the UV spectrum (Fig. 5). A comparison with a UV spectrum of a genuine starburst region (cf. Fig. 7) convincingly demonstrates that the

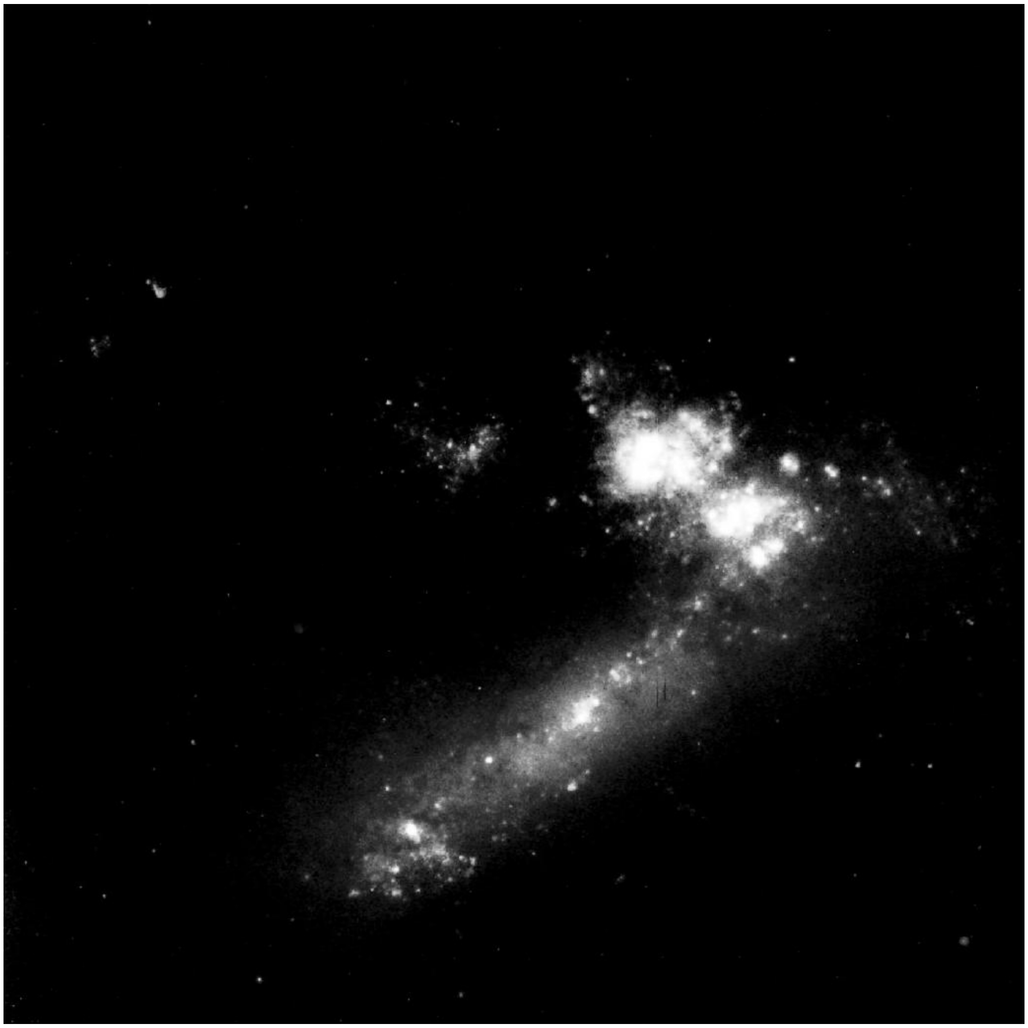

FIGURE 6. WFPC2 F439W, F555W, and F814W composite image of NGC 1741. Field size is $36'' \times 36''$ or 8.7×8.7 kpc (Johnson et al. 1999).

UV light (and the optical to near-IR light as well) comes from stars — as opposed to AGN emission. Clearly these results must not be generalized; the sample was deliberately chosen to maximize the detection probability of hot stars. Nevertheless, the HST data are convincing evidence for the ubiquity of starbursts in AGN and their energetic significance in some cases.

After showing examples of nuclear starbursts, of metal-rich, dust-obscured starburst galaxies, and of starbursts in the vicinity of AGNs, I am turning to a more typical case in the local universe. Most known nearby starbursts are hosted by gas-rich galaxies at somewhat subsolar metallicity and luminosity around and below that of our Galaxy. NGC 1741 is a well-studied example (Fig. 6). It is a member of the Hickson compact group 31 and presumably owes its current level of star-formation activity to interaction with one or more companions (Iglesias-Páramo & Vílchez 1997; Johnson et al. 1999; Johnson & Conti 2000). The dominant starburst (recognizable as the bright twin cluster in Fig. 6) is approximately 100 times as luminous as the 30 Doradus region and has an age of 4 – 5 Myr.

Massive-star formation in starbursts is an important star formation mode. Heckman (1997) estimates that about a quarter of all massive stars in the local universe form in a starburst hosted by galaxies of the types discussed in this section.

3. Stellar Content

Even the closest starburst galaxies are at distances > 1 Mpc, making studies of individual stars difficult, if not infeasible. Therefore IMF studies must often rely on less certain, indirect techniques, rather than on a stellar census. The central region of 30 Doradus is one of the few notable exceptions. Although it barely deserves the name "starburst" due to its relatively low mass of order 10^5 $M_\odot$, it is by far the closest, *unobscured* example of a region resembling a starburst galaxy nucleus. HST observations have permitted IMF determinations from the least to the most massive stars formed.

WF/PC (Malumuth & Heap 1994) and WFPC2 (Hunter et al. 1995) imagery can fully resolve the central region into stars so that crowded-field photometry techniques can be applied. The derived IMF is close to the traditional Salpeter (1955) slope. For masses higher than about 30 $M_\odot$, optical (and even UV) photometry becomes degenerate with respect to stellar mass, and spectroscopy is required. Massey & Hunter (1998) took advantage of HST's superb capabilities for crowded-field *spectroscopy* and obtained a complete spectroscopic census of the 65 most massive stars in R136, the center of 30 Dor. Their work allowed the extension of the IMF up to ∼100 $M_\odot$. 30 Dor is sufficiently massive that the upper IMF is well populated. As a result, the IMF determination of Massey & Hunter has the best number statistics in the 50 to 100 $M_\odot$ range of any observed individual stellar cluster. The high-mass IMF slope turns out to be remarkably similar to a Salpeter IMF.

The low-mass end of the IMF in 30 Dor was studied by Sirianni et al. (2000). They pushed HST WFPC2 exposures to the limits and detected stars down to about 1 $M_\odot$. The detection of stars in this mass range is significant since low-mass star formation could be suppressed in the vicinity of massive stars with their prodigious output of ionizing radiation and stellar winds. Sirianni et al. found a flattening of the IMF around 2 $M_\odot$. The overall shape of the mass spectrum at low masses resembles that of the solar neighborhood (Kroupa, Tout, & Gilmore 1993). It is not clear if the low-mass end of the IMF in 30 Dor applies to other starburst regions as well. The low-mass end of the IMF (below ∼5 $M_\odot$) in starburst galaxies is inferred from the observed mass-to-light ratio. Dynamical masses of starburst nuclei derived from rotation curves are relatively low, suggesting an absence of stars below 3 – 5 $M_\odot$ (Rieke 1991; Joseph 1999). Velocity dispersion measurements in individual starburst clusters are an alternative method for a mass estimate. Results obtained for the super star clusters in NGC 1569 and NGC 1705 indicate stars down to about 1 – 3 $M_\odot$ (Ho & Filippenko 1996). However, systematic uncertainties exist, such as virialization and equipartition.

IMF determinations in starbursts beyond the Local Group must rely on an integrated light analysis. The various techniques are summarized by Leitherer (1998). In this review I will focus on an approach which was made possible with HST's UV capabilities: analysis of ultraviolet line profiles from hot stars in the wavelength region between 1200 Å and 2000 Å. This region is dominated by stellar-wind lines of, e.g., C IV λ1550 and Si IV λ1400, which are the strongest features of hot stars in a young population (e.g., Robert, Leitherer, & Heckman 1993; Leitherer, Robert & Heckman 1995; de Mello, Leitherer, & Heckman 2000). In contrast, the optical and IR spectral regions show few, if any,

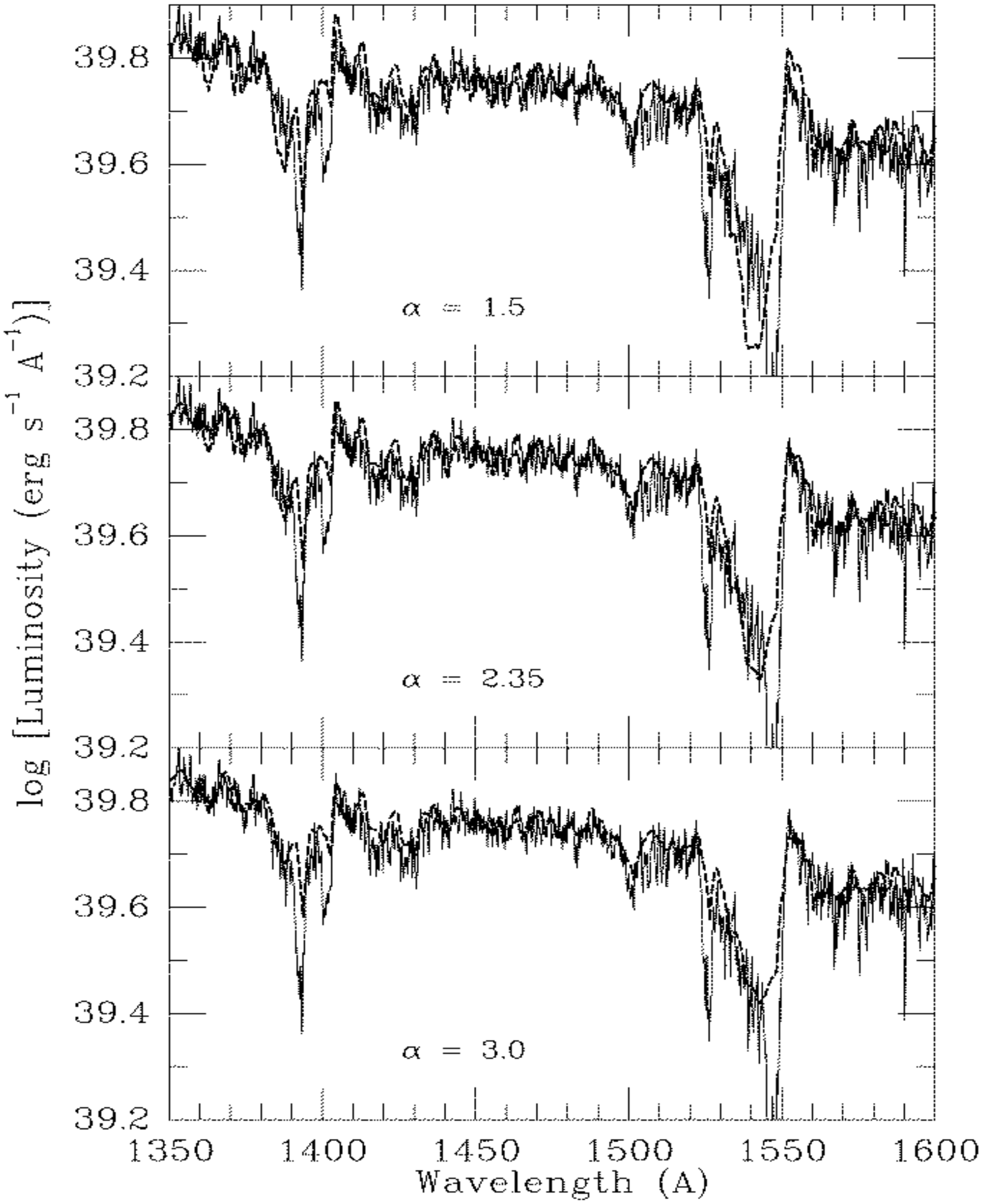

FIGURE 7. Comparison between the observed GHRS UV spectrum of NGC 1741 around Si IV λ1400 and C IV λ1550 (solid lines) and synthetic spectra for three IMF slopes (dashed lines). Upper panel: $\alpha = 1.5$; middle panel: $\alpha = 2.35$ (Salpeter slope); lower panel: $\alpha = 3.0$ (Johnson et al. 1999).

spectral signatures of hot stars, both due to blending by nebular emission and the general weakness of hot-star features longward of 3000 Å. Hot-star winds are radiatively driven, with radiative momentum being transferred into kinetic momentum via absorption in metal lines, like those observed in the satellite-UV. Since the stellar far-UV radiation field depends on the proportion of the most massive, ionizing stars, changes in the IMF

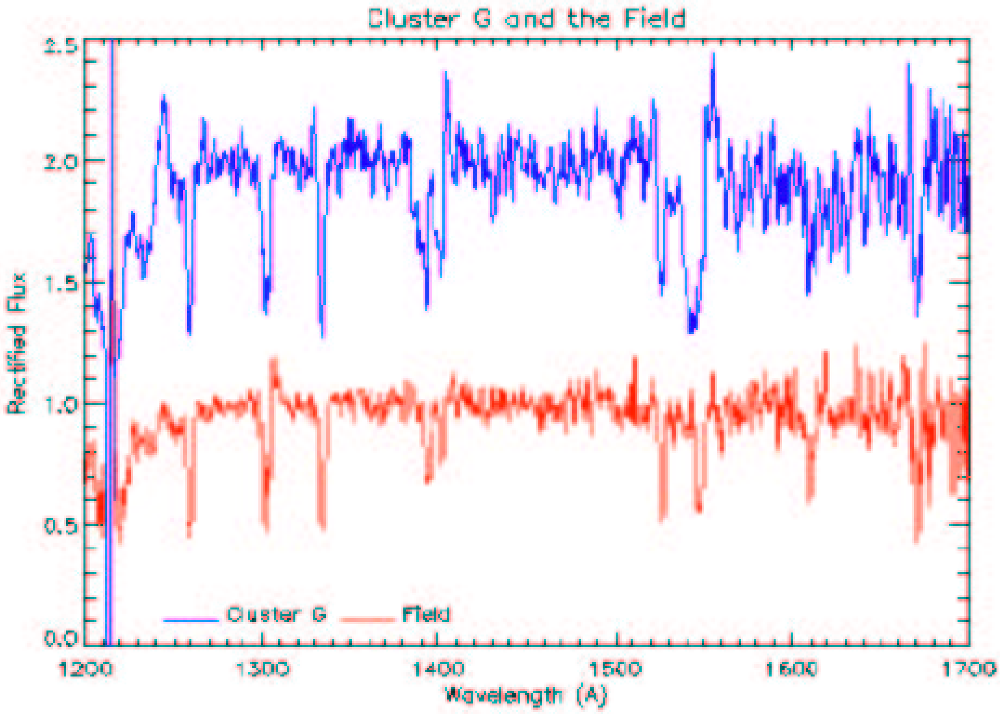

FIGURE 8. STIS UV spectra of cluster G (upper) and of the diffuse field (lower) in NGC 5253 (Tremonti et al. 2000).

and/or the age of the population can be measured as changes in the line profiles. Fig. 7 shows an example of this technique. The GHRS was centered on the southern (lower right in Fig. 6) of the two giant star clusters in NGC 1741. The spectrum was modeled with three choices of the IMF slope. A flatter slope results in a larger number of massive stars and stronger line profiles. The data suggest a slope between $\alpha = 2.35$ and 3.0, which is again close to the Salpeter slope.

Application of this technique to other starburst galaxies leads to similar results: the IMF is remarkably homogeneous, with an average slope close to Salpeter's classical value. This holds over a range of galaxy parameters, in particular metallicity. The surveyed galaxies span the metallicity range from roughly $Z_\odot$ to 0.1 $Z_\odot$, with no systematic trend of the IMF properties. This is consistent with the absence of such a trend in young star clusters and OB associations in the Galaxy and the Magellanic Clouds (Massey 1998).

A caveat remains: The galaxies studied were all UV-selected and are *on average* not IR-bright. Extension of this method to IR-bright galaxies is not currently feasible due to sensitivity limitations of UV detectors. The IMF of IR-luminous galaxies may indeed be different: the hardness of the ionizing radiation field suggests a truncation of the IMF well below 100 $M_\odot$ in these objects (e.g., Goldader et al. 1997). Alternatively, absorption of stellar UV photons by dust could be important even in the near-IR, and observations in the mid-IR would be required. ISO mid-IR spectroscopy does indeed indicate a harder radiation field than inferred from the near-IR (Rigopoulou et al. 1999).

Almost all spectroscopic studies of starburst galaxies naturally focus on the brightest galaxy region, which is the nucleus or another dominant star cluster. Meurer et al. (1995) performed an imaging survey at 2200 Å of a sample of starburst galaxies using HST's

FOC. On average, ∼20% of the light at 2200 Å comes from a population of compact star clusters, the remaining 80% are diffuse light spread all across the galaxy. The proportion of clusters versus field changes to approximately 5% versus 95% in the optical (e.g., Johnson et al. 1999), most likely the result of different population ages sampled in the optical versus the UV. A more detailed discussion of the overall properties of the star clusters and their significance for galaxy evolution can be found in B. Whitmore's contribution to this volume.

The source of the diffuse UV light could be either unresolved stellar light, or dust-scattered light from the UV-bright cluster stars. Even relatively small amounts of dust inside young star clusters can produce a strong diffuse component, observable either directly in the UV or as thermal dust emission in the far-IR. Examples are 30 Dor (Cheng et al. 1992) or the Galactic reflection nebula IC 435 (Calzetti et al. 1995).

What is the situation in starburst galaxies? In at least one case, NGC 5253, the diffuse component has been shown to be unresolved stellar light by Tremonti et al. (2000). STIS long-slit spectra of a starburst cluster and of the intercluster field are reproduced in Fig. 8. The two spectra are clearly different, therefore scattered light is not important but two distinct stellar populations are observed. The cluster spectrum is characteristic of a single population having an age of a few Myr and with massive stars up to ∼100 $M_\odot$. In contrast, the field spectrum has weak Si IV $\lambda1400$ and C IV $\lambda1550$, suggesting a deficit of very massive stars. This could be an IMF difference between the cluster and field population. Such a difference is observed in the Magellanic Clouds as well (Massey et al. 1995).

4. Evolution of Starbursts

I will focus on three topics: the triggering and onset of a starburst, the propagation of star formation, and the termination of a starburst.

The triggering mechanism in starbursts is far from being fully understood. Starbursts can be triggered by a variety of mechanisms, like galaxy-galaxy interactions, merging, secular evolution of bars, and tidal shear in the solid body rotation region (Kennicutt et al. 1987; Sanders et al. 1988; Norman, Sellwood, & Hasan 1996). The general picture is that during any of this processes, the gas in the galaxies is compressed, and while it dissipates energy, moves inward and triggers star formation (e.g., Friedli & Benz 1995; Mihos & Hernquist 1996; Hibbard 1997).

Ultraluminous infrared galaxies (ULIRG) have bolometric luminosities above 10^{12} $L_\odot$. All of their far-IR flux can be accounted for by starburst activity, with some yet unknown contribution from an AGN. ULIRGs are particularly suited to study the relationship between interaction and starbursts since most ULIRGs are found in interacting and/or merging systems (Sanders & Mirabel 1996; Sanders 1997). Borne et al. (2000) surveyed a sample of ULIRGs in the I-band with WFPC2. They identified a significant subsample showing evidence for multiple mergers. The evidence comes from multiple remnants in the galaxy cores and from the fact the some galaxies are found in dense groups of interacting galaxies. This raises the possibility that the progenitors of ULIRGs may be classical, weakly interacting compact groups of galaxies and that evolution progresses from compact groups to pairs to ULIRGs to elliptical galaxies.

An example of a case study of an IR-luminous galaxy is in Fig. 9. Dinshaw et al. (1999) performed NICMOS F110W, F160W, and F222M imaging of NGC 6090, a luminous ($L = 3 \times 10^{11}$ $L_\odot$) starburst merger at a distance of 120 Mpc. The NICMOS images are centered on the two nuclei of the merger and reveal the spiral structure of the eastern galaxy and the amorphous nature of the western galaxy. Bright knots and clusters are

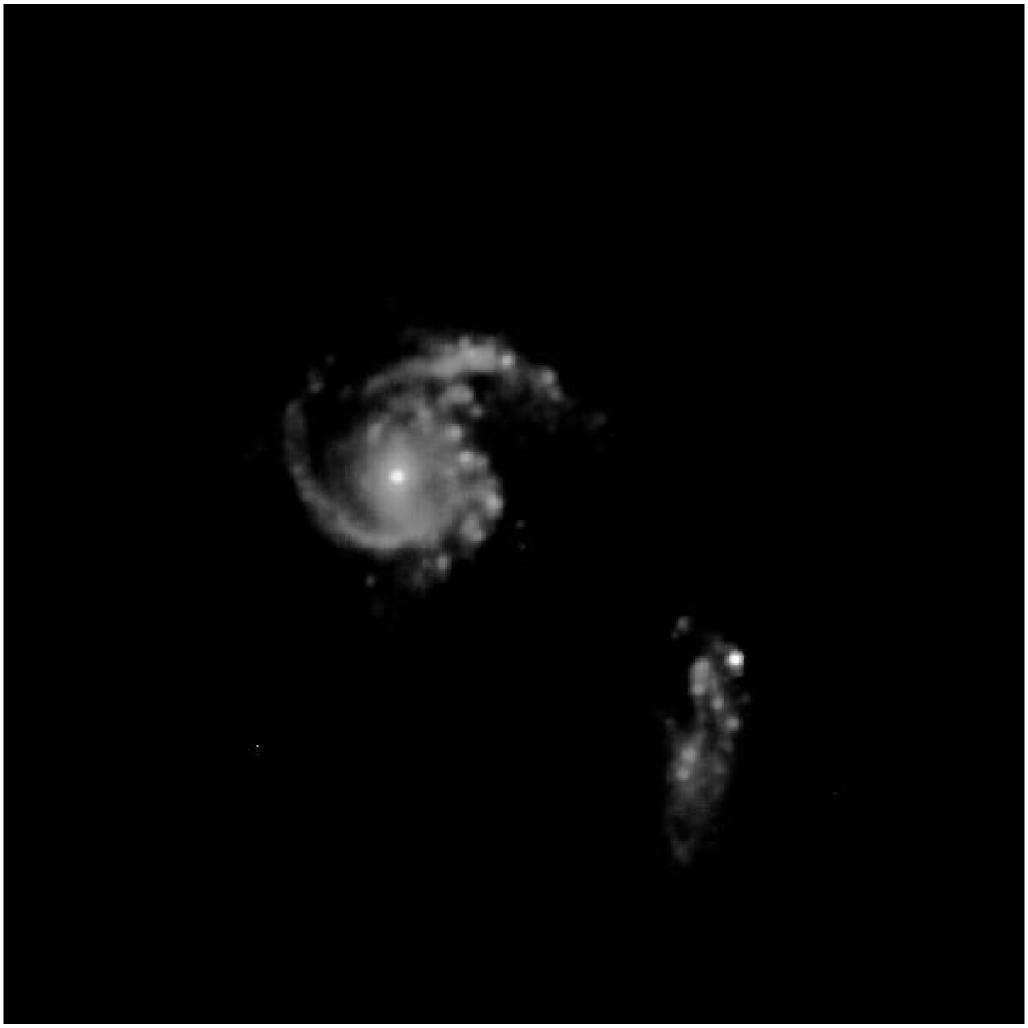

Figure 9. Three-color (F110W, F160W, F222M) composite image of NGC 6090. Field size is 15″. North is up and east to the left (Dinshaw et al. 1999).

visible in the region overlapping the merging galaxies. The knots overlap with a region where molecular gas was detected by Bryant & Scoville (1999). Much of the present star formation is occurring outside the nuclear region of NGC 6090. This is similar to what was found in other luminous IR galaxies with multiple nuclei (NGC 6240: Bryant & Scoville 1999; VV 114: Frayer et al. 1999).

Even HST cannot provide us with the spatial resolution necessary to study the "microphysics" of the star formation process in a starburst galaxy. Again, 30 Doradus is a Rosetta Stone. Walborn et al. (1999) documented an extensive next generation of star formation in the periphery of the central R136 region. Very likely, this second generation was triggered by the R136 cluster itself. Many new IR sources, including multiple systems, clusters, and nebular structures, are found. Fig. 10 shows NICMOS H, K, and narrow-band H_2 (F212N) images of several compact nebulosities. A jet-like structure is prominent in the H_2 image. The R136 region hosts numerous examples of IR-bright knots, which turn out to be groups of massive, early-type stars embedded in

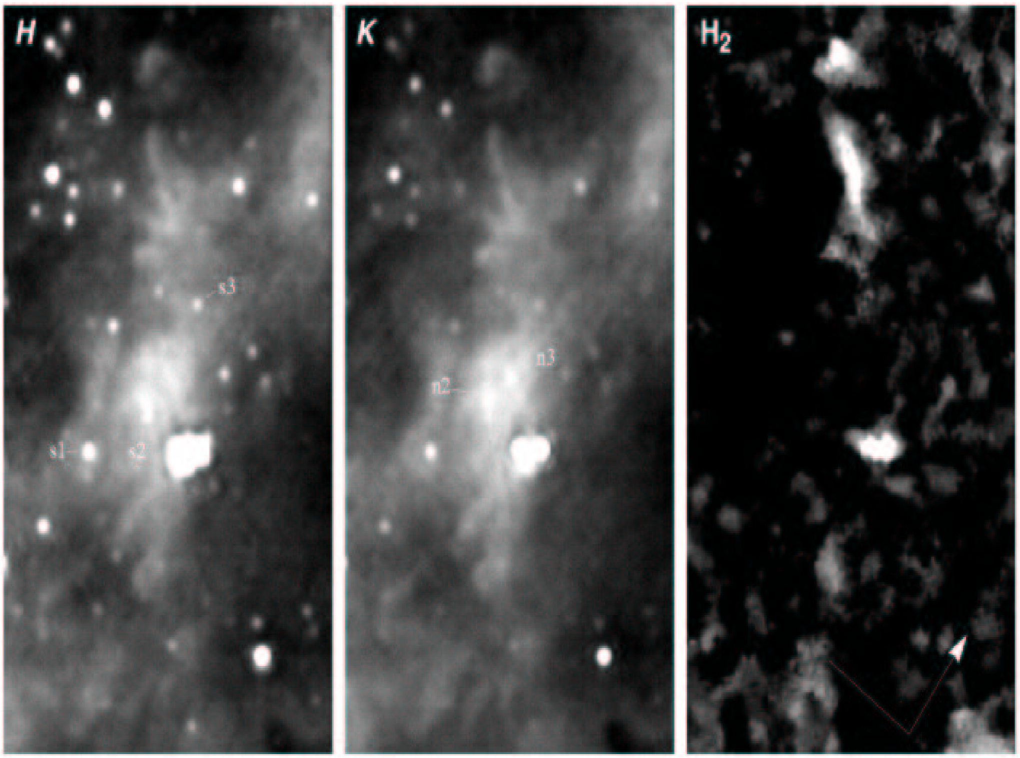

FIGURE 10. The 30 Doradus region imaged with NICMOS in the F160W (left), F205W (middle), and F212N (right) filters. The F212N image is continuum subtracted. The scale bars indicate N, E and are 0.5 pc in length (Walborn et al. 1999).

nebulosity. The most spectacular and brightest knot resides at the top of a massive dust pillar oriented directly toward R136. Other knots have pc-scale jet structures associated with them. The structures consist of detached, non-stellar IR sources aligned on either side of the stellar system. They could be impact points of a highly collimated, bipolar jet on the surrounding dark clouds. These outflows from young massive stars in 30 Dor are the first such detections outside our Galaxy. Their morphologies are strikingly similar to those seen in WFPC2 images of the Orion nebula (O'Dell & Zheng 1994) and M16 (Hester et al. 1996). These results establish the 30 Doradus nebula as a prime region in which to investigate the formation and very early evolution of massive stars and multiple systems. Star formation in 30 Doradus is not a continuous process; it occurs in multiple, instantaneous events, each possibly triggering (and terminating) the other. If 30 Doradus were viewed from larger distance, as starburst galaxies are, the decreased spatial resolution would mimic a star-formation region continuously forming stars over at least 10 Myr. Much to our frustration, 30 Dor serves as a reminder that the physical scales associated with the star-formation process in starburst galaxies may be well below HST's resolution limit.

At some point the starburst terminates. This typically occurs within less than about 10^8 yr. A hard upper limit to the starburst duration can be derived from the timescale of the exhaustion of the gas reservoir to form stars. This argument can even be used to *define* a starburst in terms of the exhaustion timescale versus the Hubble time (Weedman 1987). For a specific example consider a luminous starburst galaxy with a star-formation rate of 100 $M_\odot$ yr^{-1} (see Heckman, Armus, & Miley 1990). After $\sim 10^8$ yr, more than

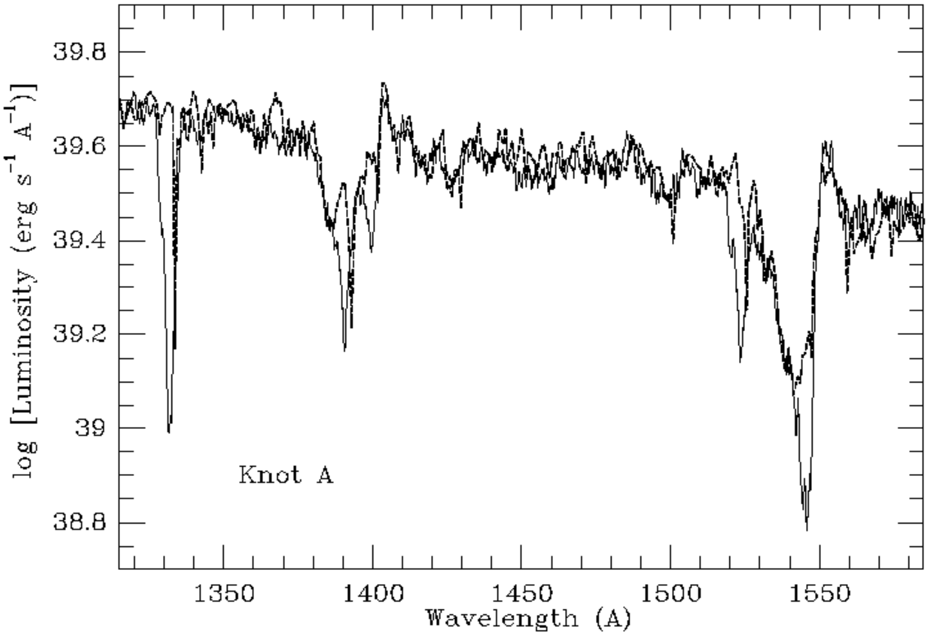

FIGURE 11. HST GHRS spectrum He 2-10. The dashed spectrum is a model fit to the *broad* stellar lines. The *narrow* interstellar lines are offset by ∼400 km s^{-1} (Johnson et al. 2000).

10^{10} M$_\odot$ of stars have been generated, which starts exceeding the total HI masses in typical $L_\star$ galaxies. The previous estimate strongly depends on the formation rate of low-mass stars, a quantity which is difficult to determine observationally. If such low-mass stars do not form (see Section 3), the time to exhaust the gas reservoir can be increased by a factor of several. Even so, it is easy to argue that a closed-box model for a starburst is too simplistic for an estimate of the available gas reservoir. Both infall and outflow should be taken into account.

An HST GHRS spectrum of the proto-typical Wolf-Rayet starburst galaxy He 2-10 is shown in Fig. 11. In this figure the observed spectrum of He 2-10 is compared to a synthetic model for a starburst age of 4 Myr. Apparently all *stellar* photospheric and wind lines are reproduced extremely well by the model. Compare, for instance, the blue wings of the Si IV λ1400 and C IV λ1550 wind lines, the standard indicators for massive stars. On the other hand, C II λ1335, Si IIλ1526, and the deep, narrow absorption components of Si IV λ1400 and C IV λ1550 are much broader and more blue-shifted in the observations than in the model. The lines are purely interstellar, arising in the interstellar medium in and around the starburst. The sharp interstellar lines seen in the model spectra can be used to measure the outflow velocity in He 2-10, suggesting a bulk motion of at least –360 km s^{-1}. The energy source are almost certainly winds and supernovae. They are capable of initiating large-scale outflows of interstellar gas via so-called galactic superwinds (Chevalier & Clegg 1985). Johnson et al. (2000) estimate that the mass-loss rate of the interstellar medium is quite similar to the star-formation rate in He 2-10. 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

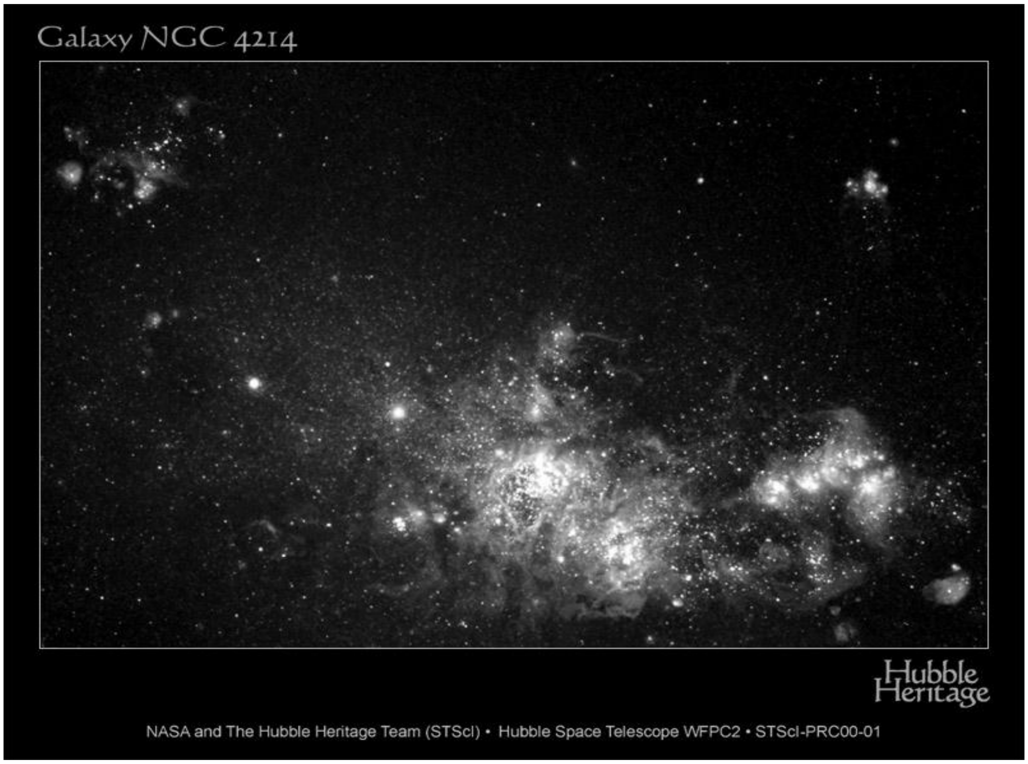

FIGURE 12. WFPC2 Hα + [O III] + optical continuum image of NGC 4214 (MacKenty et al. 2000).

interstellar material. Starbursts may determine their own fate by their prodigious release of kinetic energy into the interstellar medium.

5. Effects of Star Formation on the Environment

The impact of multiple stellar-wind and supernova events on the interstellar medium is seen via gaseous shells, bubbles, and outflows. The mechanical energy release of a hot star over its lifetime and of a supernova explosion both are of order 10^{51} erg. Initially the wind and supernova material is in a brief phase of free expansion until a sufficiently large mass of interstellar gas has been swept up. This phase is too short to be of observational significance. The fast stellar and supernova winds interact with the swept up material, producing a hot cavity, surrounded by a cool shell of interstellar material. Such shells are commonly observed around regions of high-mass star formation (e.g., Oey 1999). Depending on the mass of the central stellar cluster, their radii, expansion velocities, and ages are of order 100 pc, 25 km s^{-1}, and 10 Myr, respectively.

The nearby (d = 4.1 Mpc) irregular galaxy NGC 4214 host numerous spectacular wind-blown shells (Fig. 12). MacKenty et al. (2000) discuss Hα and [O III] narrow-band images of NGC 4214, obtained with the WFPC2 onboard HST. The HST images resolve features down to physical scales of 2 – 5 pc, revealing several young (< 10 Myr) star forming complexes of various ionized gas morphologies (compact knots, complete or fragmentary shells) and sizes (10 – 200 pc). The morphologies are suggestive of evolutionary trends: The youngest, smaller, filled regions that presumably are those just emerging from dense star forming clouds, tend to be of high excitation and are highly obscured. Evolved, larger shell-like regions have lower excitation and are less extincted due of the action of stellar winds and supernovae. Evidence for induced star formation is found, which has led to a two-stage starburst. This is similar to the sequential star formation seen in greater detail in 30 Doradus, hinting at what the morphologies of starburst galaxies at even larger distance would look like. NGC 4214 might well be a lower luminosity counterpart of some of the star-forming galaxies seen at cosmological redshift. Its spectral morphology in the ultraviolet (Leitherer et al. 1996) is strikingly similar to that of Lyman-break galaxies. Comparison of the first available spectra of bona fide star-forming galaxies at redshift ∼3 with an HST FOS spectrum of the dominant cluster in NGC 4214 convincingly demonstrated their similar stellar content (Steidel et al. 1996).

The starburst in NGC 4214 has an age of about 10 Myr or less. The majority of the newly formed stars has not had time to evolve into supernovae, and the stellar energy release is still in its early evolutionary phase. The dynamical evolution of a starburst-driven outflow on a galactic scale has been extensively discussed (e.g., Suchkov et al 1994, 1996; MacLow 1996). Initially, the deposition of mechanical energy by supernovae and stellar winds results in an over-pressured cavity of hot gas inside the starburst. This is the phase we currently observe in NGC 4214 and corresponds to the "classical" wind-blown bubble discussed above.

This hot cavity will continue to expand and sweep up more ambient material. If the ambient medium is stratified (like a disk), the bubble will expand most rapidly in the direction of the maximum pressure gradient, usually along the minor axis of the galaxy. After the bubble size reaches several disk vertical scale heights, the expansion will accelerate, and it is believed that Raleigh-Taylor instabilities will then lead to the fragmentation of the bubble's outer wall. This allows the hot gas to "blow out" of the disk and into the galactic halo in the form of a weakly collimated bipolar outflow.

Emission of Lyman-α radiation appears to be immediately related to galaxy outflows. The ionizing radiation from the newly formed young stars should lead to prominent Lyman-α emission due to recombination of hydrogen in the interstellar medium. Long ago, Partridge & Peebles (1967) suggested the Lyman-α line as an important spectral signature in young galaxies at high redshift since the expected Lyman-α luminosity amounts to a few percent of the total galaxy luminosity. Major observational efforts were undertaken to search for Lyman-α emission from faint galaxies at high redshift (Djorgovski & Thompson 1992). While *some* star-forming galaxies with Lyman-α emission were found (e.g., Keel et al. 1999; Kudritzki et al. 2000), their number is by far lower than expected from the cosmic star-formation history and line formation purely by recombination.

The assumption of Lyman-α being a pure recombination line in a gaseous medium may be too simple. Meier & Terlevich (1981), Hartmann et al. (1988), Neufeld (1990), and Charlot & Fall (1993) considered the effects of dust on Lyman-α. They found that dust scattering and absorption can be very efficient in removing Lyman-α photons from the line of sight to the observer, leading to much lower line strengths. Additionally, Lyman-α photons produced in galaxies suffer a large number of resonant scatterings in neutral atomic hydrogen. Depending on the aspect angle of the galaxy as seen from the observer, this may lead to a decrease of the Lyman-α equivalent width.

HST GHRS spectroscopy of eight gas-rich irregular galaxies by Kunth et al. (1998) indicates yet another, and most likely the dominant parameter governing Lyman-α emission: *outflows*. Kunth et al. found Lyman-α emission with blueshifted absorption in four galaxies (see Fig. 13). In these objects the O I and Si II absorption lines are also blueshifted, suggesting an outflow of the neutral gas with velocities of up to 200 km s^{-1}. The other four galaxies show broad damped Lyman-α absorption profiles centered on the

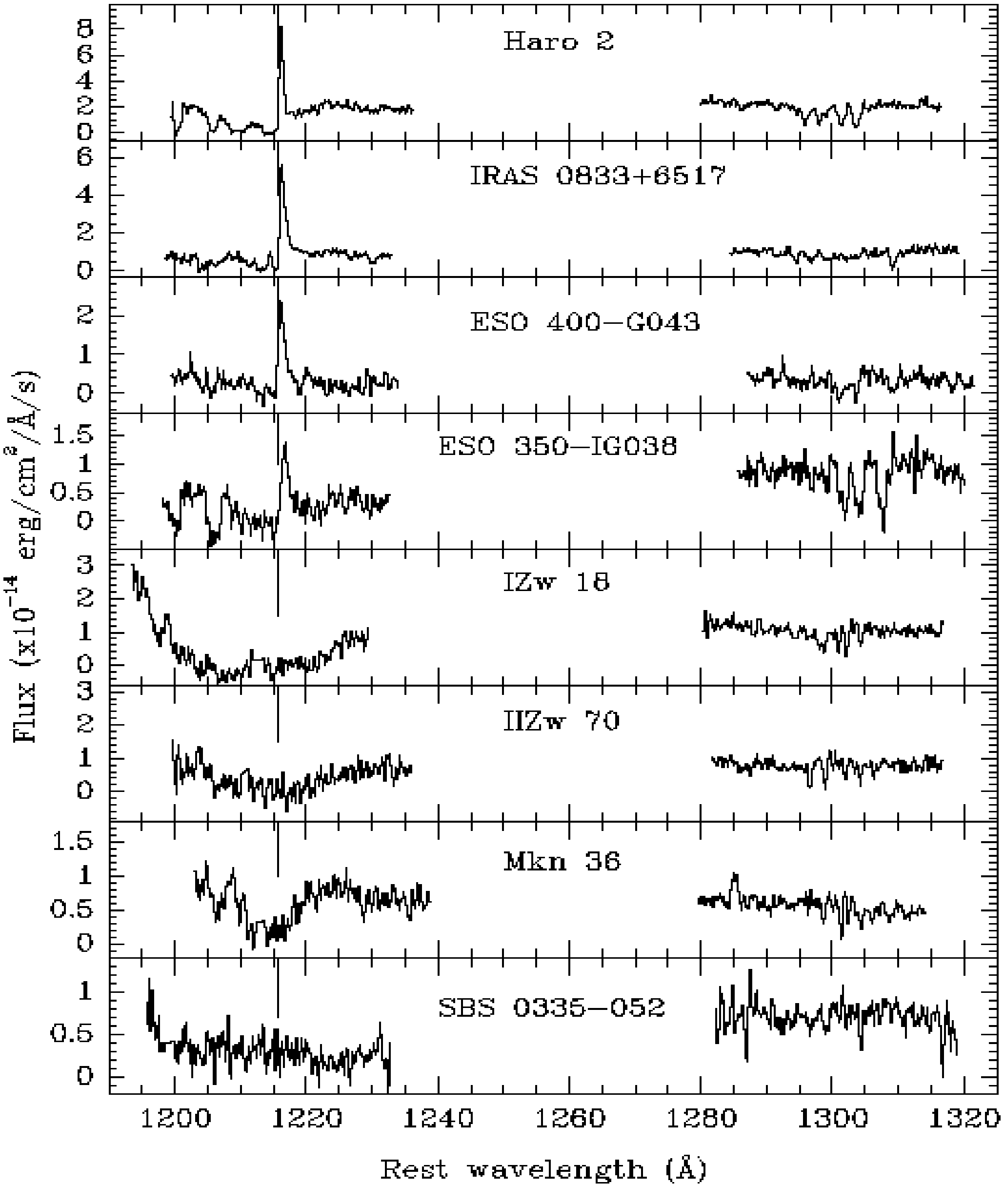

FIGURE 13. HST GHRS spectra of eight starburst galaxies around Lyman-α (Kunth et al. 1998).

wavelength of the ionized gas. The eight galaxies in Fig. 13 span a metallicity range of more than a factor of 10: IRAS 0833+6517 has solar abundance, and I Zw 18 is extremely metal-poor (~1/50 $Z_\odot$). There is no correlation between metal abundance and Lyman-α emission strength. The velocity structure of the neutral gas in these galaxies is the driving factor that determines the detectability of Lyman-α in emission. Relatively small column densities of *static* neutral gas with even very small dust content would destroy the Lyman-α photons. The situation changes dramatically when most of the neutral gas is velocity-shifted relative to the ionized regions because resonant scattering by neutral hydrogen will be most efficient at wavelengths < 1216 Å, allowing the Lyman-α photons to escape, a suggestion supported by recent models of Tenorio-Tagle et al. (1999). The implication is that feedback from the massive stars via ionization and the creation of superbubbles and galactic scale outflows leads to the large variety of Lyman-α profiles. The escape of Lyman-α photons depends critically on the column density of the neutral gas and dust, the morphology of the supershells, and the kinematics of the galactic wind. Since these effect can be highly stochastic, theoretical predictions for the Lyman-α strength are quite uncertain. Therefore attempts to derive star-formation rates at high redshift from Lyman-α emission searches are quite challenging.

6. Science Highlights: Past and Future

HST observations of starburst galaxies have advanced the subject in several key areas. As expected from its instrumental capabilities, HST made the greatest impact with high S/N ultraviolet spectroscopy and with UV to near-IR imaging at high spatial resolution. Highlights are:

- The first complete stellar census of a metal-rich, young star cluster in the Galactic Center.
- The documentation of the fine-structure in nearby starbursts down to physical scales associated with star formation.
- The universality of the upper IMF in UV-selected starburst galaxies with a broad range of physical properties.
- The detailed study of the morphology of starburst galaxies and the importance of cluster formation as a star-formation mode.
- The detection of starbursts near active galactic nuclei, and the demonstration of their energetic significance.
- Detailed studies of the feedback between star formation and the interstellar medium and the associated cosmogonic and cosmological impact.

There are good reasons to predict even brighter prospects for the next decade of HST observations. The upcoming HST instruments ACS, WFPC3, and COS will have vastly higher photon collection efficiencies. This will allow target selection driven by astrophysical requirements rather than exposure duration constraints. With NICMOS being restored, highly spatially resolved imaging can be extended to the IR. The resulting panchromatic imaging will reveal the physics of dust-enshrouded starburst galaxies. Finally, the ever growing HST Archive and Large observing programs will establish unbiased surveys of starburst galaxy properties.

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