CONFERENCE SUMMARY: STARBURSTS AND GALAXY EVOLUTION

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Abstract

Starbursts are extreme concentrations of star-forming activity with mass conversion surface densities reaching over 1000 times higher than normal for disk galaxies. They are responsible for a large fraction of all cosmic star formation. They have shaped the cosmic landscape not just in individual galaxies but though the effects of "superwinds" that enrich the intergalactic gas, constrain supermassive black hole growth, and perhaps facilitate cosmic reionization. This conference provided vivid testimony to the importance of starbursts in galaxy evolution and to the speed with which our understanding of them is being transformed by a flood of new pan-spectral data, especially at high redshifts. A key result is that it appears possible to scale the physics of smaller star-forming events upward to encompass starbursts.

1. Introduction: Solved & Unsolved Problems

"Galaxy formation is a solved problem." That was the most memorable quote from the last meeting I attended at Cambridge, the 1996 conference on the Hubble Deep Field. The prominent astronomer who offered this sentiment was perhaps a little premature, but his excess of enthusiasm was forgivable considering the stream of beautiful data on the high redshift universe that had just begun to emerge. That stream has exponentiated over the last 8 years, and it may well be that we can solve the problem of galaxy formation within the next couple of decades.

Before that is possible, however, we need to understand star formation. We have already solved the basic problem of stellar structure and evolution. That can fairly be said to be the primary accomplishment of astrophysics in the 20^{th} century (especially because it had been several million years since humans had first wondered about the stars!). There are only a few remaining dark corners of the evolutionary process. But one is crucial: star formation. This is central to galaxy astrophysics, but the deficiencies in our understanding are obvious. For instance, faulty prescriptions for star formation are thought to be the culprits in discrepancies between predictions of CDM models for galaxy formation and the observations.

A great deal of observational firepower will be directed at the problem of star formation in the coming years, but we already know one essential fact: star formation is a *collective* process. Most stars (perhaps nearly 100% in our Galaxy) form in clusters. There are strong interactions with the surrounding environment and among protostars. Quantifying feedback processes, both positive and negative, is a key to understanding star formation. All this means that star formation is a more difficult problem than was the astrophysics of isolated stars. Progress will be importantly informed by observations of other galaxies and a wider range of environments than are found in our Galaxy.

Starbursts are important because they are clearly a collective phenomenon and represent one extreme of the star formation process. Furthermore, they are bright enough to be detected throughout the observable universe and can serve as tracers of the cosmic history of star formation. This conference provided vivid testimony to the importance of starbursts as keys to galaxy evolution and to the speed with which our understanding of them is being transformed by the flood of new data, especially at high redshifts.

2. What Are Starbursts?

The term *starburst* conveys the dual notions of intensity and limited duration. There is no strict definition, however, so the term has been used (or abused) to encompass a huge variety of star formation events. Several speakers proposed useful definitions, and I will follow their lead.

Significant star formation is a hallmark of about half the galaxies in the local universe. There are several convenient proxies for active star formation: blue optical/UV colors, emission lines, or strong infrared output. Although there was a general awareness of the statistics, the Sloan Digital Sky Survey has recently brought home the unmistakable *bimodality* of optical colors: galaxies fall into either a red or blue sequence (separated by about 0.4 mag in B–V color), with few systems in between. This means they are either active star formers (blue) or have not hosted significant star formation for $\gtrsim 1$ Gyr. Interphase types are rare because once star formation ceases, color evolution from the blue to the red sequences occurs in only ~ 500 Myr (as long as the active galaxy is itself old).

The blue systems are mainly disk-dominated. The normal structure and dynamics of disks favor relatively slow conversion of gas to stars. Global *self-regulation* within disks is evidently effective over long timescales because there are good correlations between ionizing populations (lifetimes $\lesssim 10$ Myr) and broadband optical colors (characteristic times of $\gtrsim 1000$ Myr). The range of what might be called "quiescent" star formation encountered along the normal Hubble sequence is about 4 orders of magnitude in both star formation rate ($\dot{s}$, measured in $M_\odot$ yr^{-1}) and star formation surface density (Σ_{SFR}, measured in $M_\odot$ yr^{-1} kpc^{-2}). A significant number of local galaxies, mostly dwarfs, exhibit elevated activity, ranging above $\Sigma_{SFR} \sim 0.1$, which might be called "enthusiastic" star formation. This accounts for only $\sim 15\%$ of all local star formation.

The most interesting cases, naturally, are the "psychopathic" ones at the extremes, which are the starbursts. These are often, though not always, associated with a large disturbance to normal disk kinematics. The central feature of a starburst is the concentration of star-forming activity and especially the large feedback it produces on its surroundings, often driving a "superwind" out of the host galaxy. For definiteness, I will define a "major starburst" as an episode where such effects are important. This requires $\Sigma_{SFR} > 1$ $M_\odot$ yr^{-1} kpc^{-2}, equivalent to $\Sigma_{L(BOL)} > 10^{10}$ $L_\odot$ kpc^{-2} or about 1000× normal values for disk galaxies. The relevant quantities must be averaged over a finite cell size in area and time (say 1 kpc^2, 10 Myr), and the initial mass function (IMF) must contain massive stars capable of producing ionization, winds, and core-collapse supernovae.

The fact that this definition is arbitrary is actually significant: the properties of star formation regions appear to be *continuous* across the range of amplitudes observed.

Starbursts constitute an important fraction of all detected high-redshift galaxies. Because of the fierce dimming effects in distance modulus and surface brightness at large z, there is a powerful selection effect operating here. Nonetheless, statistics based on co-moving volume densities have shown that while major starbursts are rare locally ($\sim 0.5\%$ of nearby systems) they were much more common at earlier times (perhaps 15% in number and 70× in luminosity density at $z = 1$). IR-bright starbursts have been responsible for as much as 80% of the local stellar mass.

Although we don't have a definitive understanding of starbursts and their effects yet, the wealth of new data is making progress rapid. Along the way, there are two central difficulties: (1) major starbursts are rare in the local universe, and we are forced to *scale up* our understanding of physical processes from local samples and conditions; and (2) starbursts are notoriously complex 3-D systems, made especially difficult to probe by often severe differential internal extinction.

3. Are Starbursts Important?

Starbursts are certainly fascinating, but how important are they? An interesting way to frame the question is to ask: if we didn't know that major starbursts existed from direct observations, would we have difficulties explaining what we see in the universe? That is, are starbursts a *necessary inference* from other phenomena? The answer is an emphatic "yes," and here is a tentative and incomplete list of the essential fingerprints of starbursts based on issues raised in this conference:

- Super star clusters: These very massive but compact systems, ranging from very young clusters still in dust cocoons to classic globular clusters, can evidently form only in a high pressure medium, with $P/k \sim 10^{8-9}$, over $10^4\times$ higher than normal for disk galaxies. This requires abnormal, non-equilibrium conditions such as prevail in starbursts. Young SSC's are found to be mainly associated with interaction-induced starbursts.

- Massive bulges and E galaxies: The high stellar densities found in the centers of nearby early type galaxies imply conversion of large amounts of gas to stars at rates equivalent to the most extreme starbursts known, $\dot{s} \sim 1000$ $M_\odot$ yr^{-1}, if only a single event was involved. There is good statistical evidence that many, if not all, ETG's originate from gas-rich mergers, which are well known to produce violent starbursts. A few large mergers rather than a series of minor mergers are favored. (The best direct evidence for bulge-producing starbursts at early times is probably the high redshift sub-mm sample—e.g. from SCUBA—with $\dot{s}$ up to ~ 1000 $M_\odot$ yr^{-1}.)

- Cosmic mass deposition in stars: For a decade, we have been able to estimate the conversion rate of gas into long-lived stellar mass at redshifts $z \lesssim 4$. The present-day mean mass density cannot by itself place very good constraints on the range of Σ_{SFR} since over 13 Gyr have elapsed since the big bang (though, as noted above, direct statistics on distant starburst progenitors can do so). However, recent deep probes to $z \sim 2$, such as GDDS, reveal that a considerable fraction of all stars then are in "dead and red" systems comparable to local gE galaxies, with little star formation in the preceding 1.5 Gyr. The data imply that massive galaxy assembly begins early ($z_f \gtrsim$ 3–5) in dense regions and, since there is so little time for this to happen, massive starbursts with $\dot{s} \gtrsim 300$ $M_\odot$ yr^{-1} must be involved, possibly through gas-rich mergers.

The remaining items on the list involve *superwinds* generated by starbursts:

- Chemical enrichment of the ICM and IGM: Although metal abundances at higher redshifts are generally lower than prevailing local values, much of the gas to the highest z's yet probed has been processed through stars. The primordial generations of stars responsible can be explored only theoretically now, but it is clear that the natural mechanism for dispersing new metals from the halos in which they form is a superwind.

- The mass-metallicity relation in galaxies: The correlation between larger galaxy masses and higher metal abundances has been known for about 40 years. Optical, UV, and IR observations are currently providing much better information on metallicites and dust abundances in both local and high-redshift samples. Again, the natural explanation for the mass dependence is that starburst superwinds evacuate gas preferentially from lower mass systems.

- Absence of super-supermassive black holes: Supermassive black holes (SMBH) are now thought to exist in all spheroidal systems, and their masses are linked to the surrounding stellar population. Their growth by gas accretion is self-limited to the Eddington rate. Nonetheless, in the absence of another inhibiting mechanism, SMBH masses would exponentiate with an e-folding time of about 100 Myr. Star formation in nuclei is often found associated with SMBH's, and it may be that starburst winds act to regulate SMBH growth in the same way they limit star formation itself.

- Cosmic reionization: It is likely that massive stars, rather than AGN's, are responsible for cosmic re-ionization at redshifts $z \gtrsim 7$. But the optical depth in typical nearby galaxies is such that only 3–10% of ionizing photons can escape. Superwinds in protogalaxies may be necessary to clear out channels for ionizing radiation.

4. We're All Pan-Spectral Now

In the past 5 years, the necessity as well as the opportunities to attack the problem of starbursts using a multi-wavelength approach have become manifest. No single band suffices, and the full EM spectrum from radio to gamma-rays is now enthusiastically embraced in starburst research. Some examples: (*a*) stellar ages and abundances are best deduced from UV-optical-nearIR observations; (*b*) the best $\dot{s}$ estimator is $L(UV) + L(IR)$, meaning that different instruments are always necessary; (*c*) a long-wavelength baseline is essential to overcome distortions by extinction of statistical samples and of physical inferences from any given band; (*d*) starburst regions can be opaque even at mid-IR wavelengths; radio/mm observations are needed for the youngest ($\sim$ 2 Myr) embedded sources; (*e*) mid-IR photometry and spectroscopy, now just coming into their own with the Spitzer Space Telescope, show great promise as dust/gas tracers within starbursts.

Understanding the physical coupling mechanisms between wavelength domains is essential: (*a*) there has recently been good progress in modeling the UV through IR spectral energy distributions of starbursts taking all three major components (stars, gas, dust) into account, but this remains a key area for additional effort; (*b*) the long-recognized relation between radio continuum and far-IR dust emission in star-forming systems is sometimes said to be the best correlation known in extragalactic astronomy, yet we do not fully understand its origins or implications for the star formation process. A less well established radio/X-ray correlation in young systems is also important to understand.

The fastest increments in observational insight into starbursts are currently coming from Spitzer and GALEX (IR and UV). Probably the fastest increments for the coming decade will be from ALMA (mm-wave).

Although this conference emphasized observations, we cannot forget that theoretical and computational astrophysics have to be part of a “pan”-discipline approach to starbursts.

5. The Limits of Spatial Resolution

A hard lesson in the study of starbursts has been that their scales and complexities push the limits of instrumental spatial resolution even in nearby systems. For instance, it is difficult: (*a*) to measure the diameters of SSC’s ($\sim$ 2-10 pc) in order to obtain reliable mass and IMF inferences; (*b*) to study superwind substructures in nearby starbursts and to determine host morphologies in distant ones; and (*c*) to obtain kinematics of starbursts on the appropriate physical scales.

The *Hubble* Space Telescope has been the mainstay of high resolution ($\sim 0.05''$) imaging and spectroscopy for 14 years. An informal count shows that over half the contributions in this conference relied in some way on HST data. But HST will not last much more than another 6 years even if NASA can find a safe way of servicing it. In the foreseeable future, we will have the EVLA and ALMA for high-resolution radio/mm observations and JWST and ground-based AO systems for high resolution near and mid-IR observations. However, it is doubtful that AO systems will operate well for $\lambda \lesssim 1\mu$. Unfortunately, there are no current plans to replace or improve (to $\sim 0.01''$?) high resolution optical/UV capability in space. It is vital to remedy that situation.

6. Scalability

"Scalability" was a major theme of the conference. It arises from two main concerns: To what extent can we scale local starburst systems to cosmically distant ones? And to what extent can we scale the physics of modest to extreme star formation amplitudes? The evidence, fortunately, is that scalability is *good*, implying modest rather than fundamental adjustments with changes in environment and scale.

The premier example of scalability is the Schmidt-Kennicutt "law," under which $\Sigma_{SFR} \propto \Sigma_{GAS}^{1.4}$. The quantities refer to global averages over the surfaces of individual galaxies. The relation applies over a remarkable 6 decades. As noted above, a similar degree of scalability applies to the radio/far-IR correlation for star forming systems.

Other encouraging, if less firmly established, examples of scalability include:

- Congruences in EM spectral shape for starbursts across a wide range of environments and amplitudes.
- The continuity of starburst properties across a large range of amplitudes. It is possible to define a scaling sequence between the nearby (3.5 Mpc) archetypal starburst M82 ($L \sim 2 \times 10^{10} L_\odot$), more distant ULIRGs ($10^{12} L_\odot$), and high redshift SCUBA submm sources ($10^{13} L_\odot$).
- The smooth increase of starburst activity with lookback time exhibits no evidence of a *transition* point where starbursts suddenly become more important.
- Continuity of Lyman break galaxies (LBG's) at $z \gtrsim 3$ with more local systems. Careful studies, lately including GALEX data, show that properties (sizes, surface brightnesses, masses, kinematics) of LBG's are continuous with those of lower redshift luminous blue compact galaxies, some of which may be the progenitors of local dE galaxies (i.e. dynamically hot systems).
- The mass-metallicity-extinction relation, which changes only slowly with redshift and has no transition points. The abundance scale seems to decrease smoothly with redshift.

- The duration of starburst episodes is $\delta t \sim 100$ Myr and seems similar at all redshifts. Individual galaxies may experience a number of such episodes.
- The IMF for star formation on the scales of star clusters or galaxies now appears to be *universal* except in a small number of SSC's where there may be changes in M_{LOW}. The massive star IMF appears universal, which is very important for analyzing feedback processes. (Progress here has been excellent despite many complications, e.g. limited spatial resolution, large differential extinction effects, and mass segregation.)
- Star formation histories of nearby galaxies may all be similar for a given gas density, despite the presence of "noise" which gives rise to minibursts. It is important to understand the disk self-regulation mechanism.

7. Conclusion

Recent progress in understanding starbursts and placing them in the context of galaxy evolution has been outstanding and is healthily accelerating. We are fortunate to be riding a tidal wave of marvelous new data highlighted by unprecedented large sample sky surveys, HST high resolution imaging, sensitive new infrared and sub-mm instrumentation, and the inauguration of the Spitzer and GALEX observatories.

To close, let me mention some critical aspects of starburst physics that deserve special attention. How does feedback operate in young starbursts to regulate processes like saturation, quenching, and outflows? In particular regarding the latter, the largest effects of starbursts are related to galactic superwinds, but there are numerous uncertainties regarding their underlying physics. Nearby systems are the benchmarks for detailed scrutiny of superwinds. A crucial open question is the mechanism of starburst triggers: for a given trigger, there is apparently a large variation in the resulting star-formation amplitude, which remains poorly understood as yet. A final important problem concerns the drivers and time-scales for dust shroud dissipation, which transforms an IR-bright galaxy into a UV/optical-bright one. All these areas will benefit from a combined observational/theoretical attack.

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