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Conference Highlights

Star Formation from Spitzer (Lyman) to Spitzer (Space Telescope) and Beyond[1]

The confluence of the 400th anniversary of astronomical telescopes, the completion of the basic, cold, five-year mission of the *Spitzer Space Telescope,* and the near-certain advent of JWST, ALMA, and extremely large, ground-based telescopes seemed to invite a symposium to investigate the past, present, and future of star formation studies. While this summary attempts to mention everybody, with at least one significant idea from each speaker, including the one-minute poster presentations, it will surely fail. The sessions were expertly chaired by L. Woltjer, C. Cesarsky (also involved in the ESO event), J. Andersen, and H.-M. Maitzen. The Symposium started with two historical introductions (V. Trimble & B. G. Elmegreen), addressing, first, the very long time required for astronomers all to agree, only after 1950, that star formation is an ongoing process, not something that happened long ago (whether 10^7, 10^{10}, or 10^{12} years ago) when the universe was very different; and second, the vital roles of Lyman Spitzer and his immediate predecessors, colleagues, and students in establishing the existence and properties of interstellar matter from which stars could form, and the processes that would allow them to do so. Remarkably, Spitzer was never interested in the idea of cold molecular hydrogen as the raw material of star formation, and came rather late to the idea of turbulence as an important process. We follow the "seven simplest lessons from 60 years of star formation," as outlined by J. Alves, as a logical order to this summary, and invite you to keep an eye out for some of the topics of ongoing dispute, including: (a) whether the initial mass function (IMF) is universal, what determines it, and whether it is closely related to the mass distribution of dense cores in prestellar clouds (Core Mass Function, or CMF); (b) whether triggering is important; (c) whether massive stars form in the same way as ones that can remain below Eddington luminosity throughout the process; (d) environmental effects and the role of binaries; (e) how brown dwarfs form; and (f) how (in)efficient is star formation, and why. And so, on to the seven "certainties," keeping in mind that Z is metallicity and z is redshift.

1. *Stars Form Continually in the Cold Interiors of Dark Molecular Clouds (If You Doubt This, Please Leave the Room).* Multiwavelength studies of specific regions persuaded us all to remain (I. Zinchenko, on S76E, with triggering by H_{II} expansion; M. Rengel, on the second class 0 source in Lupus 3, indicating that these live for only 10^4 yr; P. Persi, on a new SF site, NGC 6334 IV (MM3); and Nakajima, also on the Lupus 3 region).

2. *Star Formation is Inefficient.* Meaning that, if you look at a particular mass of cool, dense molecular gas, the fraction of it turned into stars in a dynamical time is typically a few percent (J. Silk), though larger values are possible in bound clouds (I. Bonnell), and very different numbers probably describe star formation in galaxies very unlike the Milky Way and at large z (E. Grebel).

3. *Most Stars Form in Groups of* $10–10^6$. Cluster environments can enhance disk accretion onto planetary cores (S. Pfalzner). Brown dwarfs are more spread out than stars (S. Schmeja), though, like the evidence for mass segregation as clusters age, this surely has some contribution from source confusion in dense centers.

4. *There Is a Characteristic Product, a Log-Normal IMF, Peaking at* $0.2–0.3\ M_\odot$. Though this, too, could have been very different long ago and far away (Grebel). Also, low-mass stars are single (R. Jayawardhana on Cha I and Upper Sco, also providing a candidate for the first directly-imaged exoplanet); in contrast to Herbig AeBe stars, most of which are binaries, their disks aligned with their orbit planes (R. Ooudmaijer).

5. *Feedback Processes are Ubiquitous and Important.* There are jets at all wavelengths (K. Stapelfeldt, on numerous new Herbig-Haro objects detected by *Spitzer*), the need for ongoing supernovae to keep star formation down to the observed 2% (J. Silk), and perhaps even massive star feedback to form clusters (J. Alves).

6. *Stars Form with and from Accretion Disks Across the Full Mass Range from BDs to OBs.* And there is a definite time sequence over which the disks disappear (I. Tsukugoshi, on T Tauri stars). There are also evolutionary sequences in maser type, radio emission, and SED shapes (R. Oudmaijer). Whole clusters also evolve (S. Schmeja) from hierarchical to centrally-condensed structures.

7. *Nature Does Some "Prepackaging."* So that the distribution of core masses, the CMF, has the same shape as the IMF (though shifted to larger masses), and must somehow give rise directly to the IMF (J. Alves). This was perhaps the topic of greatest dispute among the "certainties." Several speakers asked whether the CMF predicts the IMF (R. Kawabe, reporting several AzTEC/ASTE surveys; R. Smith, noting that different methods yield different observed CMFs; P. Hennebelle, remarking on the range of relevant processes, with outflows, accretion, and turbulence of comparable importance; and S. Dib, suggesting that the transformation from CMF to IMF is a function of environment). I. Bonnell firmly denied a direct link between

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CMF and IMF, once one allows for continuing fragmentation as well as more accretion.

Not yet at the level of eternal verities are the primacy of massive stars in the formation process (with disk accretion, competitive accretion, and stellar collisions and mergers in environments of increasing density, according to R. Klein, and the private opinion of VT), and the need for all the processes you can think of (gravity, angular momentum transfer, magnetic fields, accretion, turbulence, feedback–this is either the good news or the bad news, depending on how you feel about programming). But the probability that there is no further missing physics counts as good news.

Then came four outstanding review talks, two from observers, two from theorists (and if you are organizing a seminar series this year, try to get at least one of these speakers!). First, K. Stapelfeldt provided an overview of the *Spitzer* mission, the five-year cold part of which is essentially over, but a two-year "warm" extension, during which the two shorter wavelengths will still be usable, has been approved. *Spitzer* is currently about 1 AU from Earth, drifting backward, and eventually will not be able to turn in the right direction and send us data.

Among the discoveries important for star formation have been:

1. Seventy percent of infrared dark clouds have embedded protostars (and those that do not could have BDs, or might eventually disrupt).
2. At least one region has remarkably gray dust with $A_{24\ \mu\mathrm{m}}/A_K = 0.44$; there is spectroscopic evidence for many kinds of grains, including large ice-mantled ones.
3. Water is found in many places as vapor or ice; there is also acetylene.
4. The statistics of class 0, I, and II sources are not quite as expected.
5. Disks with central holes, perhaps due to planets, are fairly common.
6. Protostellar disks last for 10^7 years, and debris disks, for 10^8 years; debris disks imply that agglomeration has proceeded at least as far as planetesimals, comets, and asteroids.

Second, E. Grebel absolutely blasted through the very different contexts in which star formation occurs, from starbursts down to dwarf galaxies, pointing out the different rates, patterns, efficiencies, and probably IMFs, and the evidence for different modes in common galaxy types, as observed or as inferred from the resultant star populations. Continuous, episodic, or one-shot star formation occurs depending on gas content, mass density of the galaxy, and interactions or accretion. Some other points she made (far from a complete list) include:

1. Stars are now forming in S and Irr galaxies, in galactic centers, and in interacting galaxies. Star bursts process $100\ M_\odot\ \mathrm{yr}^{-1}$, and ULIRGs, up to $1000\ M_\odot\ \mathrm{yr}^{-1}$.
2. Typical spirals form $20\ M_\odot\ \mathrm{yr}^{-1}$, much larger than the Milky Way value of 1–3 $M_\odot\ \mathrm{yr}^{-1}$.
3. For many gE's, the rate is roughly $0\ M_\odot\ \mathrm{yr}^{-1}$, but about $1/3$ have evidence (including Galex UV colors) for active rather than passive evolution; that is, for some ongoing star formation.
4. Field gE's have their oldest stars about 2 Gyr younger than cluster gE's.
5. $E + A$ galaxies indicate cessation of star formation at a definite time in the past.
6. The Milky Way has a number of discrete stellar populations, distinguished by age and Z, including: globular clusters (not themselves all the same), two sorts of field halo stars, two sorts of disk stars, and a bulge.
7. There was a time gap between the end of halo and the beginning of disk star formation in the MW which is not understood; the bulge stars are mostly older than 10 Gyr and have [Fe/H] across the range -2.0 to $+0.5$.
8. Most large galaxies show age and metallicity gradient.
9. It is not clear whether Irr galaxies have massive halos; the star velocity dispersion is close to rotation speed, and HI tends to be spherical (consider maps of LMC).
10. IR galaxies host 10–20% of current star formation.
11. There are tidal tail galaxies and BCDs (with HI and star formation concentrated at their centers).
12. Dwarf galaxy SF is very inhomogeneous, and you can see pollution by single SNe as scatter in relative abundances.
13. The ratio of s to r products is an age indicator.
14. Winds are important.
15. Star formation in the outskirts of S's is not understood.

Third, J. Silk described the multitude of physical processes that must be considered in theories of star formation, the evidence for them, and some of the outstanding questions. Key issues include the IMF, star formation efficiency, turbulence, quenching, and triggering. Among the points he made were:

1. The IMF is not necessarily constant, and if it was top heavy at large z, this will affect the SFR(z) derived from any tracer.
2. The mass assembly history derived from *Spitzer* and star formation histories derived by other methods disagree at $z = 3 - 4$; differences in stellar M/L (the IMF) are a likely cause.
3. Core velocities are mildly supersonic in the ρ Oph region; more generally, porosity of the ISM is self-regulated, so that star bursts have high turbulence and low porosity, while quenching occurs with low turbulence and high porosity.
4. The percentage of gas in GMCs is also regulated by turbulence.
5. Quenching is due to different processes on different scales and in galaxies of different masses, for instance, to fountains and outflows on large scales in normal galaxies; but to BH ac-

cretion, jets, and radiation in AGNs, whose activity is quenched at the same time, corresponding to the well-known black hole–bulge relation.

6. Triggering is seen on assorted scales, but is not universal.
7. AGNs can also enhance star formation by compressing gas, and the SFR depends on interactions between hot and cold gas.
8. Downsizing means both that big halos formed first, and that the ratio of (SFR)/M (already in stars) declines toward the present from $z = 2.5$. The process is perhaps magnetically regulated.

Fourth, the primary discussion of star formation calculated from numerical simulations came from I. Bonnell, for whom the key questions are the why's of star masses and the IMF, of inefficiency, and of clusters vs. distributed SF; and the how of core properties giving rise to star masses. On this last point, he firmly concluded that, because of ongoing accretion plus fragmentation, it is very unlikely that there is a 1:1 relation between core mass and stellar mass. Initial conditions are obviously important for these simulations, so that the *Spitzer* survey of GMCs (the stage where $\rho = 10^{-17\ldots-21}$ g/cm^3) is vital input. Other things that matter include binaries and disks. Most star formation occurs in bound structures, where low-mass stars and BDs form from gas falling into the cluster, while high-mass stars result from rapid accretion (slowed but not stopped by feedback) in incipient cluster cores. Bound gas clouds have SFE around 15% vs. 3% for unbound clouds.

Several of the shorter contributions were of direct relevance to these issues, for instance: high-resolution mapping of Av in Barnard 59 as a probe of SF efficiency (C. Roman); the need (in calculations) for external confining pressure to keep gas together and allow small length-scale fluctuations to grow (J. Dale); the dominance of small separations and mass ratios near one for low-mass binaries (R. Jayawardhana); and the significantly larger luminosities of ultracompact HII regions compared to massive YSOs (R. Oudmaijer).

And the future came at the end. We heard about several ongoing and upcoming projects, including,

1. The APEX, Atacama Pathfinder, which sees known SF regions, starless cores, hot molecular cores, IRAS sources, embedded clusters) and CH30H maser sources, for which follow-up searches with Effelsberg, IRAM, and Mopra yielded only one non- detection, a planetary nebula! (F. Schiller)
2. SOFIA is coming, with a call for proposals due in 2008 December (M. Hannebush), and more about SOFIA from R. Klein, who pointed out that one of its major goals is to identify the dominant formation mechanisms for massive stars, though he left the impression that everything that anybody has suggested happens somewhere.
3. An all-sky map of Galactic GMCs now in progress, derived from 2MASS extinction measurements (J. Rowles)
4. A concept study for a 4 meter space telescope usable from mid-UV to near-IR (R. Jansen)
5. A survey of Gould's belt (primarily the diffuse material, not the OB star) with HARP on the JCMT; and SCUBA-2 is coming in 2009 (J. Hatchell)
6. ALMA, for which L. Testi described the science goals, required capabilities (in terms of millimeter/submillimeter resolution of 0.1″ and sensitivity sufficient to map CO and [CI] over the entire Milky Way), and timeline. But, he said, it will neither image exoplanets "nor solve the star formation problem" (partly, one suspects, because it is a little difficult to decide just what "the" star formation problem is).

Our grandest view of the future came from M. McCaughrean, who emphasized the facilities that will become available over the next decade or two, including: ALMA, the large, ground-based E-ELT (plus the TMT and GMT); radio facilities like e-MERLIN, LOFAR, and SKA; and in space, the upgraded HST, Herschel, SOFIA, GAIA, and KEPLER. But, he concluded, the most important new facility will be JWST, with a five-year mission promised and the potential for another five years before gases and such run out. He indicated that the single most important thing it has to offer is greatly improved angular resolution, and that, similarly, in planning the new, large ground-based telescopes, the best possible angular resolution is more important than pushing into the thermal infrared. Goals are 0.01–0.1″, though one can make this sound more impressive by speaking of 10–100 milliarcseconds. Some of these facilities will return data by the tera- and petabyte, so that improved capacity for number receiving, storing, processing, and crunching will also be vital. An interesting case (not mentioned) is LSST, where the decision has to be made just how much raw data can be kept, so that, for instance, if a flare occurs in a star formation region somewhere far away, one can go back over the past years' images, where the source may have been a two-sigma, three photon smudge, and determine how bright and how variable it was previously.

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