Panel discussion I: Star formation in galaxies: how do we continue?

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Abstract.
This is the written account of the first of two panel discussions, on Star formation in galaxies: how do we continue? The chair of the panel was Phil James, and panel members were John Beckman, Torsten Böker, Daniela Calzetti, Angeles Díaz, and Rob Kennicutt. The panel and audience discussed the four following questions: 1) What are the most critically needed techniques to give accurate measurements of total rates and efficiencies of star formation? 2) Do we understand the form of the initial mass function and its variation as a function of redshift and environment? 3) Are there multiple modes of star formation in galaxies (bulge vs. disk, burst vs. continuous) or does the Schmidt law explain everything? 4) How do we bring together our understanding of star formation in our Galaxy and in external systems?

JAMES: (Introduced the panel members, then introduced the four questions, and asked John Beckman to give his opinions on the first: What are the most critically needed techniques to give accurate measurements of total rates and efficiencies of star formation (SF)?)

BECKMAN: Rob (Kennicutt) and Daniela (Calzetti) will have more to say on this topic but I will make some remarks to start the discussion. One question is on missing photons: which fraction of the SF rate (SFR) might be missed due to escaping photons when we observe a whole galaxy (assuming that the initial mass function [IMF] issue is covered). We know that photons can easily leak out of HII regions, but most will get soaked up somewhere in the galaxy so the global SFR should take them into account anyway. But there is a caveat. In grand design galaxies in particular, a large fraction, up to 50%, of the emission may be diffuse. This should not be missed but the diffuse emission can easily fall below the detection threshold. Locally this is most probably not a problem, but it might well be more significant at higher redshifts.

DíAZ: I would like to stress the importance of high accuracy in measurements. A second point is that we then need similar accuracy in the tools we subsequently use for analysis. We need to know and quantify the influence of, e.g., leaking photons, but also second order effects which we must take into account as the observations become better. We also need to analyze the scatter which may well carry physical information.

KENNICUTT: To me, the key is the issue of efficiencies. Thanks to the multi-wavelength revolution in observations over the last few years we now have a lot of information on many different issues. But I worry about our knowledge of the interstellar medium, about molecular masses involved, and about cloud
cores. New facilities like CARMA and ALMA are coming, but we need experts to say where improvement is most needed.

BÖKER: A main outstanding question is that of recent versus current SF. Even Hα gives information on the “past” SF, and to observe the current SF we need sub-millimeter observations. This is not yet being incorporated into the discussion on SFRs.

CALZETTI: Among the advances that new millimeter telescopes and instruments (ALMA, LMT [Large Millimeter Telescope], CARMA) will bring is the possibility of detecting CO emission in the interarm regions of galaxies, another under-explored region of the parameter space of galactic environments.

JAMES: Thank you panel members. I now invite comments from the audience.

KRUMHOLZ: I would like to comment on questions (1) and (4), and stress that we need to worry most about, and clarify, the efficiency of SF. In a Galactic context, the term efficiency is used to describe the fraction of mass which is transformed into stars over the lifetime of a cloud. But in an extragalactic context, efficiency is used to denote the SFR over gas mass, which is an instantaneous measure and not one over a lifetime. My comment, then, is that we should rather not use the term efficiency, or define carefully whether we are talking about instantaneous efficiency or over a lifetime.

HENSLER: I agree with Mark (Krumholz) but let me add that a galaxy is not a closed box, and so in addition we need to consider how, e.g., infall influences the efficiency.

SHETH: The new CARMA telescope is now working, and early work on M51 shows that it works very well. But rather than concentrating on HCN, we should use 1 mm continuum which is where the improvements in CARMA are the most significant compared to OVRO/BIMA and other observatories. The 1 mm continuum would trace the dense dusty regions in galaxies.

EVANS: A worry is whether even with ALMA we will be able to sort out observational issues to obtain molecular gas masses to a precision better than a factor of three. In particular the calibration of CO measurements is difficult and we need simulations of molecular clouds in galaxies to understand what the observations mean and what their real uncertainties are.

CHURCHWELL: IR observations are sensitive to the most massive young stellar objects (YSOs), whereas X-ray observations are sensitive to magnetic activity in lower mass YSOs, so together one has a chance to determine the IMF for the whole stellar mass range within a given cluster. It’s the lower mass range that has historically been the most difficult to establish and since most of the mass is in lower mass stars, this is the most important part of the IMF that needs to be determined with good precision. My student is trying to use the GLIMPSE survey to determine the current global SF rate in the Galaxy, but to do this he has to determine the IMF, especially for lower mass YSOs, for various environments in the disk of our Galaxy. Our hope is that X-ray data from Chandra and other X-ray satellites will provide the tool to do this.
Lehnert: I would like to address the differences that we heard on Monday between the results on SF modeling, from Mark (Krumholz) and Ian (Bonnell). We need to know how SF happens in different environments within and outside the Galaxy, and the key point is how do we approach this.

Krumholz: The difference is mainly due to a limitation in the CPU power we can use. Ian (Bonnell) can model larger volumes because he doesn’t include the effects of radiation.

Lehnert: ...but are you sure you know the physics?

Krumholz: The limitation is in the code and in the CPU, not in the physics.

Kroupa: We’ve heard earlier in the week (in the talk by Alves) that the stellar IMF shape is already found in the mass distribution of the cloud cores. But theoretical work seems to be wrong, for instance I quote the failure of Klessen, Spaans & Jappsen (2007) to reproduce the mass function of the Arches cluster. This is very worrying indeed, and we need more work on the theoretical side.

Bonnell: The Klessen et al. result of a top-heavy IMF depends primarily on their input assumptions of the dust physics and background radiation field. I would not misconstrue their result as implying we do not understand the dynamics of the star formation process, but rather that there remain many unknowns that are still input into the numerical simulations.

Alves: I propose the use of a combination of the extinction technique, which is easy and works well in local clouds, with the study of clouds at larger distances as described by Churchwell on Monday. The prospects of this combination are good, but it won’t be easy.

Evans: I totally agree. The cores we see in local clouds go up to $2 - 3 M_\odot$ in mass and have nothing to do with massive SF. Up to now we cannot resolve the much larger cores, and even with ALMA this will be very tough.

James: I propose that we move on to point (3): Are there multiple modes of SF in galaxies (bulge vs. disk, burst vs. continuous) or does the Schmidt law explain everything? Let’s hear from our panel members.

Beckman: Before going to point (3) I would like to add something to the discussion on the previous point, namely that the correspondence between the IMFs as derived from cloud cores and stars is almost too good to be true - and let’s hope it is indeed true. This makes the theorists’ life much easier, all they will have to do is scale... I think the measured turnover in the stellar IMF to low masses, plus the turnover in the mass function of the cloud cores in João’s (Alves) work is clearly one of the key novelties so far in this meeting.

James: On to point (3) then - we should discuss whether the Schmidt-Kennicutt law is really the last word, or whether it may in some sense be holding back new developments in this area, and whether we should thus look to move on to a more physically grounded approach (while still citing Rob (Kennicutt) appropriately)?

Beckman: Rob?
Kennicutt: I'm thinking on my feet here... In yesterday’s talks we heard about SF in nuclei, we know now that this occurs over scales of hundreds of parsec, and is involved in the formation of bulges. We have heard of central SFRs of up to 1000 $M_\odot$ yr$^{-1}$. It is remarkable that one law can cover all this range of SF, from the very low-mass regime to the extremes just mentioned. I wonder whether we have any evidence that there is more than one mode, or more than one phenomenon. Does the single Schmidt law reflect a single universal mode of SF, or could there be two or more modes that happen to follow the same dependence of SFR and gas surface densities? I guess the answer in this respect is very much like we have discussed already with regards to the IMF: we don’t see any evidence for a change, but we should be astounded if indeed there weren’t any.

Beckman: Suggestions on whether there is evidence from abundance ratios for more than one mode of SF come and go – does anyone know what the current state of affairs is?

Böker: The SF mode that produced bulges in the early Universe must be different from the currently dominant one: a stellar mass in the order $10^9 - 10^{10} M_\odot$ was formed in a very short time.

Kennicutt: Or for example how did a globular cluster like M13 or Omega Cen form? Have we seen anything at this conference that is relevant to SF in that context?

Díaz: Considering clusters of 1000 $M_\odot$ (not 1000 $M_\odot$ yr$^{-1}$!), do we have there a violent mode of SF, such as the one that Rosa (González-Delgado) talked about? It cannot simply be adding up lots of little SF events, this doesn’t seem to work so we must have another mode of SF.

Calzetti: I would like to present a concrete example on how observations can sometime be misleading in the interpretation of the modes of SF. Back in the mid-90’s, analysis of UV images of nearby starburst galaxies led to the discovery that only a small fraction (about 20% or less) of the UV light was associated with clearly identifiable stellar clusters; most of the UV light (~80%) was associated with a diffuse stellar component. During that period, the hypothesis was advanced that SF had two “flavors” (modes): a cluster mode and a “diffuse” mode. Subsequent studies, over the course of the following 10 years, have shown that the diffuse UV component is likely the “product” of the dissolution of the stellar clusters over timescales of about 10–20 Myr; once the clusters have evaporated, the UV light will appear to be originating from a diffuse stellar population. Hence, there appears to be one single mode of SF in starbursts, the “cluster” mode.

James: Let me restate the question posed by John (Beckman): is there any evidence from stellar abundance ratios for the existence of different modes of SF?

Silk: In this respect, we remain biased by the local Universe. Even if we can cope with objects like M13, we continue to have big problems at high redshifts.

Bastian: Looking at smaller scales, we know from a decade of star cluster research with the HST that there are not different modes. The relations between
the SFR and the number of clusters present, and similarly the relation between
the SFR and the mass of the most massive cluster in the galaxy argue strongly
that “starbursts” and quiescent galaxies lie on the same continuum. In addition,
work done by myself and also by Bruce Elmegreen has shown that star clusters
themselves are simply part of a continuous distribution of SF in galaxies, from
sub-parsec to kpc scales.

Böker: This is a valid point, but it refers to the very local Universe, and
to the current SF. The past may have been very different.

Nesvadba: We looked at the SF in detail in one galaxy at $z \sim 2.6$, as close
as we can at present at high redshift (Nesvadba et al. 2007). We found a SFR of
$\sim 500 M_\odot \text{yr}^{-1}$, and no evidence for an AGN contribution (which includes the
X-ray). The SF efficiency we found is very similar to that found at low redshifts,
which implies that the SF properties are very similar. The same is in fact true
for the SF-related feedback. There are obviously limitations working at these
redshifts, but empirically, we have not found alarmingly large discrepancies.

Krumholz: A comment on the differences in the IMF. If the expected
number of low-mass stars were present in the ring around the Galactic center
(given the observed number of B-stars) we should have seen X-ray emission from
them, but haven’t.

Hammer: We don’t even know if there is a Schmidt law at $z \sim 0.6$. Indeed
the gas distribution has a big effect on this law, and we know that there is much
more gas at a redshift of unity. How is this gas distributed? I am not sure that
question (3) is relevant.

Capuzzo-Dolcetta: May I stress that even after the talk by Kennicutt
it is not clear what the Schmidt law actually means physically. As it stands, it
is a phenomenological law.

Edmunds: I wonder why we must go on about variations in the IMF. The
point is that it is fair enough that the IMF changes in strange places like the
Galactic center or the metal-poor early Universe. But we don’t have to change
the overall IMF – this is great science!

Lehnert: The Schmidt law has been alluded to as an empirical one, but
the question is what keeps the SF inefficient. It may be related to the effect of
shear (cf. Mark Krumholz) due to differential rotation in the large scale velocity
fields of galaxies, which will be much lower in the central parts with solid body
rotation. So, what will control SF in these regions? And why do spirals look
young, but disks look old?

Balcells: Let me put on a theorists’ hat. I would then want the SF to
depend on dynamical parameters, such as the velocity dispersion. Gas clouds
should collapse in different ways, and I would like to have a parameter that
prescribes when the gas can become molecular. For instance, in ellipticals the
gas is too hot so it won’t form stars. Similarly there is gas at the centers of
spirals but it cannot collapse. All this should really go into the Schmidt law,
but in that case will it still work?

Kennicutt: There are examples of that, e.g., the Silk law (which relates
the SFR density to the ratio of gas density and dynamical time, and thus iden-
ifies the number of “compression events”, or the number of times the gas goes through the spiral arms). We have tested this, but there is no clear signature. For instance, in disks the SF declines exponentially with radius, but the velocity dispersion profile is flat with radius. So yes we do need to move to a physical basis of the Schmidt law, but Occam’s razor tells us that density alone does the trick.

SARZI: About star formation in early-type galaxies, it is interesting to notice that the objects that for sure experienced recent SF all have gas emission characterized by very small velocity dispersion, independent of the apparent ionization of the gas, as traced by the $[\text{O} \text{III}]/\text{H} \beta$ line ratio.

KRUMHOLZ: In response to Marc Balcells: there is no lack of theoretical ideas, quite to the contrary, there are perhaps more theories than theorists. There are papers by, e.g., Klessen, Silk, and myself on how the Schmidt law may be related to the underlying physics.

SILK: I agree that the Schmidt law is a very good fit and is a great result, but the more interesting physics is in the scatter.

DÍAZ: Indeed, we should perhaps concentrate on those objects that do not fit the Schmidt law and then try to find the physical drivers that made them deviate.

CALZETTI: We studied M83 in detail to test this possibility. If the interesting environments to study are those where SF deviates from the Schmidt-Kennicutt law, then the outer regions of galaxies need to be excluded from those studies. The combination of recent data in H\text{I} (from the VLA, data obtained by Fabian Walter), mid-infrared (from Spitzer), and UV (from GALEX) of the outer regions of M83 suggests that the UV emission in those extreme environments is associated with SF that is compatible with the Schmidt-Kennicutt law. Those regions are located at a distance from the center of about four times the H\text{α} cut-off radius of M83.

BECKMAN: Partially in answer to Mike Edmunds’ point: the interest lies in trying to identify the objects that do not fit the relation, and then to find the physics drivers for them.

JAMES: I wonder if there are any further comments, because we need to finish in five minutes. Would anyone from our panel perhaps wish to comment on the fourth question: How do we bring together our understanding of SF in our Galaxy and in external systems?

CALZETTI: When I formulated question number four last night, this is what I had in mind. We have seen during the course of this conference that there is a direct (linear) correlation between SFR and dense cores. I believe this implies that we are moving the problem from having to explain physically the Schmidt-Kennicutt law in its original formulation, to having to explain the correlation between the density of dense cores and the total gas density.

KENNICUTT: If I refer back to the introduction of Neal’s (Evans) talk, I think we need to come together in our studies of the small and the large scales. Perhaps the key to tying the Schmidt law to the underlying physics lies in
detailed studies of SF at small scales. So Neal, let me put you on the spot: what should we observe?

**Evans:** We need to speak, first of all, a common language, use a common terminology, especially on issues of efficiency and timescales. There is a difference between whether, and how fast, you make stars, and on large scales SF tends to be slow. Remember that the actual process of SF occurs in dense cores, which are two steps removed from the scales where the Kennicutt-Schmidt relations operate. First, you need to understand what controls the formation of molecular clouds, which is probably best studied with very high resolution and sensitivity (ALMA and CARMA) in nearby galaxies. Then you need to understand what controls the fraction of a molecular cloud that turns into dense cores (a few percent in local molecular clouds, but maybe very high in extreme starbursts). This is probably best studied in our own Galaxy, but it requires a careful combination of observations with models. Those two approaches together may bridge the gap.

**Sheth:** May I take the opportunity to advertise a conference organized by the Spitzer team in Pasadena this autumn, where we plan to bring together these two communities, and where we hope to start answering these questions.

**James:** Our time has run out, so may I ask John Beckman to make a closing comment?

**Beckman:** It is great to see more people getting together to discuss these themes, the more people together, the more we think we know. There are many new observational results, for instance multi-wavelength determinations of SFRs using GALEX, Spitzer and other facilities, and also on gas and its detailed structure. So the observations are getting better. There still seem to be too many theories so what we must perhaps think of are observational results that cannot be reproduced by any theories.

**James:** With those words we finish this panel discussion. Let me thank our panel members, and the members of the audience.

**References**

Klessen, R. S., Spaans, M., & Jappsen, A.-K. 2007, MNRAS, 374, L29
Nesvadba, N. P. H., et al. 2007, ApJ, 657, 725