Massive Star Formation: Observations Confront Theory
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Summary of Panel Discussion II: Theoretical Models and Observational Constraints in High-Mass Star Formation

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Abstract. This paper presents a summary of a panel discussion to more directly confront theoretical models and observational constraints in massive star formation research. The panel was moderated by Hans Zinnecker, and panel members included Ian Bonnell, Chris McKee, Francesco Palla, Malcolm Walmsley, and Harold Yorke. Additional ample discussion with the audience is recorded.

1. Concept and Introduction

This is a summary of the second panel discussion at MSF07 conference in Heidelberg on Sept 13, 2007, entitled: Theoretical Models and Observational Constraints, which lasted about 90 min. Hans Zinnecker was the moderator of this discussion. The invited participants of the panel included the following five distinguished massive star experts: Ian Bonnell, Chris McKee, Francesco Palla, Malcolm Walmsley, and Harold Yorke (almost all theorists). The idea was to first give the word to the panelists who would each raise and discuss the one observational question which they found most interesting and important. In the second part the audience, now stimulated, would be invited to join the discussion and ask their "tough" theory questions to the panelists or suggest further observational homework to us all. This more or less worked, and people can refresh their memory of what has been said via the video of the panel discussion available at `http://www.mpia-hd.mpg.de/MSF07/`.

At the very beginning the moderator took a few minutes to introduce the subject by displaying the three basic models of massive star formation: monolithic collapse, competitive accretion, and stellar mergers (cf. Zinnecker & Yorke 2007; Beuther et al. 2007). He then asked the question which observational constraints could be placed on the various models and whether massive star formation is or is not a scaled-up version of low-mass star formation. He surmised that all the models could be mutually correct and applied to different circumstances of massive star formation. Thus, the analogy is that three theoretical models set forth could be imagined as the two sides of the same coin, plus its rim.

2. Key questions from the panelists

The moderator suggested Malcolm Walmsley to go first, followed by Chris McKee, Ian Bonnell, and Harold Yorke (in that order), and Francesco Palla at the end.

Walmsley, after admitting that he is still confused, chose his outstanding question to be the following: *What are the accretion rates onto massive protostars, and how can we best imagine to get an estimate?* Three types of accretion flows must be distinguished, that from the disk onto the star (not yet observed), that through the disk (enabling gravitational torques), and that onto the disk from a protostellar envelope. In a time-averaged sense, all these mass accretion rates should be the same. He referred to the talks of Yorke and Hosokawa whose results showed that different amounts of accretion onto the central star make a big difference in the stellar evolution (see also their contributions to this volume).

McKee, addressing his question to the observers in the audience, asked: *Is turbulence universal and what drives it?* He referred to his own turbulent core model (i.e., monolithic collapse model) for massive star formation as one in which turbulence is driven, while the competitive accretion model is characterized by an initially high level of turbulence which then decays. He referred to the review of MacLow & Klessen (2004) for a discussion what can be the drivers of turbulence. As time goes on, using increasingly sophisticated computer codes we might come to a concensus. While we know that there is more turbulence on larger scales (e.g., the mm observations of Chris Brunt presented at this meeting), he emphasized that we need to know much more about the smaller scales. He challenged the observers to find out which kind of turbulence is more typical: driven or decaying?

Bonnell, after starting with a funny analogy for competitive accretion (go to a busy restaurant instead of an empty one!), raised the key issue: *Is all massive star formation clustered?* In the competitive accretion model, all massive star formation is linked to cluster formation, and the answer to the question would be YES. He suggested observations to look for clustering statistics around stars of (say) greater than $10\,\mathrm{M}_\odot$, and referred to the work of Weidner & Kroupa (2006) on the maximum stellar mass as a function of the cluster mass, but also pointed out that Elmegreen disagrees with this work.

Yorke, after endorsing Walmsley's question as a primary question that he too would have posed, found himself left with a second important question, viz. *Is the upper IMF and the maximum stellar mass universal?* He wondered why the upper IMF in the Orion Nebula Cluster and in the R136 cluster in the LMC could be the same. He emphasized that very high angular resolution is needed to be sure we are observing stars and not whole unresolved star clusters. He also wondered whether a 1:1 mapping of the molecular core mass function, which looks similar as the IMF, can really be true, given the very high multiplicity fraction of massive stars.

Palla, alluding to homework for the next conference on massive stars, presented us and himself with the following final panelist question: *Is high-mass star formation first or last?* In other words, he asked: what is the sequence of events, e.g., in the making of a star cluster, and are there ways to discriminate the order in which low-mass stars and high-mass stars form? He emphasized two aspects: (1) what are the accretion rates for low-mass and high-mass stars? (2) It seems clear that often they form together in the same environment (clusters).

The moderator used his prerogative to interfere and proposed to have a poll at this point to the panelists requesting to answer Palla's question by a show of hands. Malcolm was in favor of "last", Chris and Ian (miraculously) agreed "at the same time", Harold also held "at the same time" while Palla voted for "last" - as did the moderator, who added his comment that if massive stars formed first (which none actually claimed) we would have a serious problem with radiative feedback which would destroy the parent cluster cloud and prevent low-mass star formation.

3. Additional questions from the audience

In the following, we summarize the questions and comments received from several members of the audience, including reactions from the panelists and the moderator.

Tan: I'd like to take issue with Ian Bonnell who said that the turbulent core model and the competitive accretion model are not so different after all. I think there is a big difference. In the turbulent core model the gas gathers first. My question to the observers would be: can we try to catch protostars with (or without) gas mass around them and find out whether such gas is bound to the star?

Churchwell: 1) How does matter get onto the central star? We don't know. 2) How can massive star formation proceed in isolation? How to prevent fragmentation?
Yorke reply: ad 1) We don't know for low-mass stars either, nor for AGN.
Palla reply: ad 2) With new survey data (like Spitzer), we will be in a better position to estimate the fraction of isolated massive stars.
McKee reply ad 2) Some massive O-stars are found in small groups. There seem to be low-mass clouds producing untypical IMFs - Krumholz and McKee are exploring this scenario, where a high threshold pressure rules. Fragmentation is prevented when the accretion rate is very high, causing gas heating.
Bonnell reply: ad 2) Even with heating (later on), initially there is no heating to prevent fragmentation.

Shepherd: I think we have to iterate between observations and theory to get the correct answers. For example, what is the outflow rate and the turbulent feedback from massive stars? Can theoretical simulations help us to correct the observations?
Yorke reply: maybe in 4 years but not in the immediate future...
McKee comment: We also need surveys as to the generality of turbulence.

Krumholz: I believe where we did make progress in the last few years is whether star formation is slow or fast. Observers can go out and test how the rate of star formation depends on gas density and environmental factors. The rate of star formation has implications on the mode of star formation (Krumholz & Tan

2007). It is about 1% of the cloud mass per free-fall time, thus it is slow... there is no evidence that it would accelerate with time...
Bonnell comment: ... too bad Bruce Elmegreen is not here ...
Palla comment: ... I am Bruce Elmegreen! Bruce did not say that star formation is short-lived, he said two modes coexist in giant molecular clouds (GMCs): one is on the dynamical timescale, but the way it gets there is slow (i.e., there is another, longer timescale due to the fact that GMCs have envelopes which are less dense). Now I am Palla: You also have to study the stars (not only the gas) to find the star formation rate, particularly in clusters!
Henning: Bruce Elmegreen was here two weeks ago at a summer school, he should have stayed on. We discussed the IMF of cores and the IMF of stars. We noted that the core IMF stops at 8-10 $M_{\odot}$, i.e., massive cores are rare or don't exist. The maximum core mass known is 23 $M_{\odot}$, how do you form a 50 $M_{\odot}$ star from it?
McKee reply: It is true that we have not found the high-mass cores yet. The prediction, however, is that ALMA will find hundreds of massive cores in the future at large distances. It'll also unravel the structure of GMCs...
Walmsley reply: The core mass function is a tricky business, as a core has no clear edge; the density profiles are such that most of the mass is near the edge. We need a better definition of "massive cores".
Bonnell comment: Charlie Lada's work on the Pipe Nebula seems to suggest that low-mass cores are unbound, while high-mass cores are bound... (Lada et al. 2008).

Vazquez: Not only cores are not well defined, but clouds as well ... they are shredded and have no clear boundaries. – I also have a question to the observers: can we see large-scale organized flows? (cf. Hartmann & Burkert 2007's model for the collapse of the entire Orion cloud). Can we discriminate purely random turbulence from focused turbulent flows? It appears that driven and decaying turbulence are not so different in large-scale organized flows.

Burton: ... on the core mass function ... a warning to the theorists: different search algorithms give different core mass functions. We really have no idea!
Zinnecker: One should give the same set of data to two independent groups and perform blind tests.

Bally: Changing the subject ... We heard about the Arches, the Quintuplet, and the Westerlund 1 cluster which hosts a magnetar (black hole). Can we produce black holes by runaway mergers as modeled by Portegies Zwart et al. (2004)?
Zinnecker comment: Runaway mergers are hard to achieve in even the densest observed clusters... but who knows maybe it is possible in galactic nuclei...
Bally (continued): What are the precursors to globular clusters, why don't we see them in the Milky Way?
McKee reply: In the Antennae, the pressure is much higher: you have a million solar masses squeezed into 1 pc in size.
Yorke comment: In the Antennae, yes; but you also have M82 or 30 Dor. It is not an easy question to answer, it is not just pressure.

Zinnecker continued: The initial conditions for forming globular clusters must include lots of gas swept together quickly...
McKee comment: Here is another theoretical challenge: globular clusters have virtually the same stellar IMF and characteristic mass, despite very different conditions from present-day star formation (e.g., metallicity).
Schulz: The point was raised whether high-mass star formation was a scaled-up version of low-mass star formation. What about intermediate mass stars?
McKee reply: Our turbulent core model makes a link between low-mass and high-mass star formation: the thermal sound speed must simply be replaced by the turbulent sound speed for the higher masses. As for the issue of outflows: the same MHD theory applies for low-mass and high-mass stars, which makes unique testable predictions for hypercompact HII regions (i.e., outflow-confined bubbles).
Yorke comment: There are similarities but also differences. It is significant that there is no break or knee in the IMF but rather a gradual smooth change-over from high-mass to intermediate-mass and on to low-mass stars. There is one big difference: intermediate-mass stars end up as white dwarfs, high-mass stars as supernovae.
Palla comment: Not sure about the IMF at the highest masses: there could a break at (say) 30–50 $M_\odot$. The poor sampling at the high-mass end does not allow us to make strong statements.
Zinnecker comment: If stellar collisions start to play a role for the highest masses (e.g., the merging of tight massive binaries), then the upper IMF could have a gap before the maximum mass (the merger product) is reached.

Hoare: Why was triggered star formation so low on the list of topics? There is ample evidence from multi-wavelengths galactic surveys that young massive star formation is triggered. I want to make a plea to return to study triggered star formation. We are planning an IAU Symposium in Rio 2009 on this.
Zinnecker comment: There was an IAU Symposium dedicated to this subject at the General Assembly in Prague in 2006. If I remember correctly, there was no concensus on the issue ... the problem is to prove a spatial and temporal causal relationship between the triggering agent and the triggered result. In the case of the Upper Sco OB association, the evidence is compelling, but in other cases it is circumstantial (cf. Preibisch & Zinnecker 2007).

4. Concluding Remarks on Methodology

Karl Popper's falsification principle: In his concluding remarks, the moderator wanted to leave the audience with a philosophical thought, challenging the methodology of our daily scientific work where we tend to find the observational evidence that we look for to corroborate our favorite theory. It would be more convincing to find evidence contrary to what we set out to look for. He quoted Sir Karl Popper (1902-1994) who in 1934 in his book "Logik der Forschung" suggested that a theory can never be verified or proven but can only be falsified or disproven. What does this mean for the progress in our field of science? It means that progress comes from an iterative process, where observations not only confront theory but also theory predicts observations. The latter can then be critically checked by new key measurements (experimentum crucis) and can be used to select an improved but still incomplete theory (there is no final theory). Actually, it would be even better if we subjected ourselves to an even more self-critical methodology where observations confront observations (for example at different wavelengths) and theory confronts theory (for example simulations with different numerical codes). Hopefully these cautious words will keep us on track in the frantic race for new results!

References

Beuther, H., Churchwell, E.B., McKee, C.F., Tan, J.C. 2007, Protostars & Planets V, p. 165
Lada, C., Muench, A.A., Rathborne, J., Alves, J.F., Lombardi, M. 2008, ApJ 672, 410
MacLow, M.M. and Klessen, R. 2004, Rev. Mod. Phys. 76, 125
Hartmann, L. and Burkert, A. 2007, ApJ. 654, 988
Portegies Zwart, S., Baumgardt, H., Hut, P., Makino, J., McMillan, S.L.W. 2004, Nature 428, 724
Preibisch, Th. and H. Zinnecker 2007, IAUS 237, 270
Krumholz, M. and Tan, J, 2007, ApJ 654, 304
Krumholz, M. and McKee, C. 2008, accepted for Nature, astro-ph 08010442
Weidner, C. and Kroupa, P. 2006, MNRAS 365, 1333
Zinnecker, H. and Yorke, H.W. 2007, ARA&A 45, 481

The panel of the second panel discussion.