Galactic Star Formation Across the Stellar Mass Spectrum
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Discussion Summary

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1. Introduction

One of the challenges concerning this meeting was to find a way to actually make it a "workshop" even though the interest in the meeting yielded such a high attendance (about 120 participants). The SOC did not want the attendees to spend four days simply being lectured to, but at the same time thoughts of creating work groups or doing anything hands-on was restricted by the large attendance. The idea decided upon by the SOC was to have a daily 30–45 minute discussion of the topics covered each day. Even so, with such a large group, there was the fear that the discussion would be dominated by a few pundits arguing back and forth. To the contrary, these sessions proved to be forums where many people aired their ideas and concerns regarding our current understanding of star formation, and at least I view these group discussions as a success. On behalf of the SOC, I would like to thank Paul Ho, Guido Garay, Luis Rodríguez, and Hans Zinnecker for leading these four stimulating discussion sessions.

I decided to record these discussions to see if anything could be included into the book of proceedings that might benefit those who were unable to attend. The following is not a word-for-word transcription of these discussions, but a summary of the major topics covered. I think you will find that many of the topics discussed expose our present limits of understanding in the field of star formation as a whole, and point us in the direction of further research.

2. IMF Studies

The Initial Mass Function is certainly a crucial component to any discussion of star formation across the full spectrum of stellar mass. Therefore, are the observational astronomers getting the data that the theoreticians need and want concerning the IMF? More specifically, are there enough data to accurately model IMFs presently, and if not, what types or quality of data are needed? The general audience opinion was that complete and unbiased data sets are too few at present. The slopes of the IMF in the extremely low mass and high mass regimes are not yet well known. IMF studies that are presently available are also riddled with large errors from several factors such as completeness, and also from systematics like crowding and faint star corrections. Not until a large number of data sets with small errors are available will we begin to correctly address issues such as whether or not there is a universal power law in the IMF, and whether or not the Salpeter law extends into the lowest and highest stellar mass regimes. Some studies do exist addressing these issues, such as IMF slopes in the brown dwarf regime, but still data seem to be conflicting.

This predicament of errors and biases also needs to be addressed before we can answer the question: Is there a "universal" IMF? Our discussion came to the conclusion that *if* there is universality, it is a broad-brush definition, sweeping a lot of variations under the rug which at this point may or may not be real, or may be properties that are poorly categorized, or ill-understood. IMF data from different stellar clusters *do* scatter, but it appears that there is going to be some average IMF that has a broader validity, i.e. comparing large scale IMF measurements of different parts of the Galaxy or between galaxies. However, one must be careful in comparing cluster IMFs to the field IMF. Clusters tend to be fit by Salpeter laws by observers, and the field IMF is also just a bunch of clusters itself, but mostly *small* clusters, and this will yield an IMF that is steeper than Salpeter and different from cluster IMFs.

Related to the universality of the IMF, another major topic addressed was the effect of metallicity. So far there is no observational support of an IMF variation due to metallicity. Suggestions were made for producing IMFs analyzed in the same way from different environments within the Galaxy, such as the Galactic Center and far outer Galaxy. Perhaps this issue can be addressed with field populations of different ages. Again, however, field populations may be too limited in mass coverage to deal with issues of IMF in the lowest and highest mass regimes. Clusters of different ages may be the only way to obtain information concerning *all* of the IMF issues as a function of metallicity. There is agreement, however, that the errors of any such endeavor must be small to be truly useful.

There has been increasing evidence pointing towards the idea that the IMF of pre-stellar clumps in molecular cores is very similar to the stellar IMF. What are the implications if this is true? It was agreed that a larger sample of data is needed, but that the shape of the clump IMF and stellar IMF are indeed similar. This would imply that star formation efficiency is similar across all stellar masses. Furthermore, because the clump masses would be similar to the final stellar masses produced by the clumps, this implies that star formation efficiency is very high, contrary to accretion theory. Hot molecular cores have a few 100 to 1000 solar masses, and therefore must lose a lot of that material, because stars that big do not exist. It was argued that even low mass star cores have been observed to have too much mass, so there must be a material removal process (e.g. winds) to remove some of this excess. Contrarily however, it is pointed out that hot molecular "cores" may contain several forming stars. Furthermore, outflow studies by McKee and collaborators have shown that there do indeed exist sources of high star formation efficiency. In any event, this similarity of clump and stellar IMFs appears to be a concept that challenges modern ideas of how stars form, and will certainly simulate more study in the future.

Returning to the originally posed question and summarizing the discussion of IMFs effectively were the final comments of Richard Larson. He points out that the problem with theorists predicting anything concerning IMFs presently is that the observers try too hard to make their data fit theory, for example, with non-uniform analyses and by binning data until it resembles the theory. In other words, because the errors are large enough, data can be "bent" to fit theory too easily. What is really needed is a robust, model-independent way of analyzing data that all observers use, so that it can then be compared in an unbiased way to IMF theories.

3. Star Forming Cores

What are the density profiles of star forming cores? We have four models: the simple isothermal, the logotropic, the polytopric, and Bonner-Ebert definitions. Each of these is density dependent, therefore proper fitting will not only determine densities for the cores, each model also will imply different mass infall rates. Therefore, quantifying the density profiles of cores is an important tool in deciding how stars form. Which is correct, or do we believe that high mass cores are best fit by, say, logotropic profiles, whereas low mass cores are better fit by, say, isothermal profiles? Are we having problems determining density profiles, or are *none* of these good descriptions of the density profiles? Simulations by Vázquez-Semadeni have not been able to reproduce logotropic profiles, even though observations of hot cores *have* been shown to be well-fit by logotropic profiles. The reasoning is that for high mass stars there is a lot of mass in a small space, and thus hot cores are highly centrally condensed, compared to low mass star forming cores, and are thus well fit by logotropic profiles. Though logotropic models do not make sense thermodynamically, they are perhaps useful as a phenomelogical fit to observations, and viewed in this way it have some utility.

Contrarily, Shirley showed at this conference that his sub-mm observations implied approximately the *same* power law for both higher mass stars and low mass stars ($r^{-1.6}$). He states that the previously seen logotropic sub-mm profiles were most likely influenced by the beam pattern of the telescope. However, it is pointed out that the resolution of the observations so far are not good enough to accurately determine density profiles of the most massive stars, i.e. in hot cores.

It is concluded that in order to address this issue, a consistent set of observations over a range of masses with high-resolution needs to be performed. There is promise that SMA (and eventually ALMA) will help address this issue by being able to probe down to small scales the dust density profiles over a large range of object masses and very close to the centers of the cores in the submillimeter.

4. Isolated vs. Clustered Star Formation

Does star formation occur in isolation or in clusters? Of course the answer appears to be both, and it appears mass dependent, i.e., low mass stars tend to form in isolation, whereas high mass stars tend to form in clusters. However, it was pointed out that the spatial scale is an important issue when discussing isolated versus clustered star formation. For instance, low mass stars *do* appear to form in loosely aggregated groups on spatial scales larger than 0.5 parsecs, but if you look at spatial scales smaller than ~0.1 parsec, formation certainly appears in an isolated core. Likewise in the case of high mass stars, one can say that they form in isolation if you look at a small enough scale of ~0.01 parsec, where you can see individual, dense star forming clumps. So there is a semantics issue here: it appears that one can say that star formation is always clustered and always isolated, it simply depends on the scale that you are talking about.

But do stars ever form in "real" isolation? Are there any good candidates of young stars that do *not* exist in clusters and that have *no* companions? It is pointed out that some Bok globules, which are very young and small, *do* appear to be very isolated. These may be candidates for evidence that stars can form in isolation for low mass stars. However, as with trying to prove any negative, it would be very hard to prove for sure if a star did form without a companion of some kind.

5. Disks and Disk Evolution

What determines the timescale of disk evolution and do all disks evolve by forming planets? We have seen in this workshop that the evidence points to the fact that low mass stars dissipate their disks in 3–6 million years, and for high mass stars the dissipation factor seems to be smaller only by a factor of 2 or 3. If disks *always* form planets, the problem then becomes: How does one maintain the disks that we see? Models of coagulation within disks show that once planet formation begins, it is a very fast process. The timescale to go from dust to objects that are large enough not to be seen effectively in the infrared is on the order of thousands of years, and the timescale to go to planetesimals is of the order of tens of thousands of years. So once planet formation is triggered, the dissipation of the disk goes fast. Observationally, the disk dissipation timescale seems to be on the order of 100,000 years, hence something keeps the disk from dissipating. Boss has models that agree with this idea that disks evolve in a very short period once planet formation begins. He suggests that disks will disappear quickly once they are no longer supplied with material from their infalling envelopes. Once the envelope is cut-off from the disk, the material within the disk probably spirals into the central star, or goes into mass sinks within the disk, or gets blown out of the system; all on a very fast timescale. Therefore it is suggested that the disk lifetime is probably controlled in a large part by the supply of material from their placental clouds.

On the other hand, there are A-type stars that are in relative isolation, that don't appear to have a large reservoir of material around them, and are on the order of 10 million years old and *do* have disks. If disks dissipate so quickly, why are we still seeing these disks around these older sources? The problem with comparing these "transition disks" (like TW Hydra) to accretion disks is that the reservoirs for the two are different. Accretion disks are fed solely by material in an envelope spread out over a large volume, whereas transition disks may have a large portion of their material coming from asteroid collisions and comet debris. The reservoir of material in these transition disks is made up of larger bodies that are much harder to observe.

Of course there is also the issue of the effects of environment on the lifetimes and evolution of disks. You *do* see shorter disk lifetimes on average for stars in OB associations, because not only do you have the protostars trying to dispel their disks themselves, but you also have ionizing radiation and outflows from the nearby O stars decreasing the disk lifetimes. Then in a few million years the first supernova in the association goes off, blowing away all the material in the association, thus starving the disks of the members. This would explain why the disk lifetimes in OB associations like Orion are observed to be shorter than for Taurus.

Furthermore, most stars form in binary and multiple systems or in otherwise crowded environments, and this could equally well explain quick disk dispersals from dynamical interactions with the member of these systems. Many binary and multiple star systems have separations of the order of 30 AU, so disks *could* exist at the 5–10 AU size in these systems, but would have very short lifetimes (thousands of years) unless there is a circumbinary reservoir to feed them. GG Tau is an example of this. It is two stars with circumstellar disks surrounded by a circumbinary disk. They are T Tauri stars and hence rapidly accreting. The circumbinary disk *must* feed the individual disks in order for them to be maintained. It has also been speculated that tidal interactions in these binary systems can heat disks so that coagulation of planets will not occur. Therefore, not *all* disks should form planets.

What range of sizes do we expect disks to have? Why are some silhouette disks around the low mass stars in Orion so large ($\sim$1000 AU)? First it was pointed out that *most* silhouette disks around low mass stars are of the order of 100-300 AU, which is what we typically think of when we are discussing the sizes of circumstellar disks. It is also pointed out that the size-scale of the largest disks around low mass systems is of the order of the size of the disks in massive stellar systems. These sources have disks resolved on the order of a few 1000 AU (i.e. IRAS 20126, which has also been seen to be rotating in CH_3CN). There are also 10,000 AU ammonia structures that have been observed around young high mass stars that look like huge rotating disks or tori. Maybe there is, in these cases, an inner $\sim$100 AU sized accretion disk and these large tori are feeding them. We cannot know for sure until the inner regions can be directly observed and resolved. Maybe something like this configuration is happening for the lower mass stars as well, thus explaining the large silhouette disks we see around low mass stars in Orion.

This leads us to the last question regarding disks: Have we found accretion disks around O stars? It is agreed that the answer is no. Again, we *do* see large tori in, say, ammonia around stars, as well as elongated envelopes around massive stars in the mid-infrared. These are some larger envelopes of material that may or may not be related to the central accretion disks of these objects, however in both cases we do not directly see the central disks. If massive stars are indeed formed via accretion like lower mass stars, then there are several reasons why we have not seen actual accretion disks around them yet. First, massive star forming regions are so far away that it is difficult to see small scale structures. Second, by the time we can detect a young massive star in the sub-mm or mid-infrared, they have already cleared their central environment. We need to detect massive stars at even *younger* phases to catch the disks. Some groups are already working to find these sorts of candidates for follow-up with SMA and ALMA which will be able to probe these even younger objects very close to the central massive star.

6. Our Solar System as a Model for Star and Planet Formation

Many people believe that the 'Solar Nebula' from which the planets formed was the remnant of the accretion disk that surrounded the primitive Sun. If so, how does one account for the fact that the Sun's equator is inclined at about 7 degrees to the invariable plane of the Solar System? There can be a few reasons for this. First, most stars form in binaries, multiple systems, and clusters. In fact, one could account for all single stars easily if they were originally in triple systems and were ejected. Therefore, just like any typical star, the Sun probably formed in a dense, complex environment with significant interactions with neighboring stars, or in a small multiple system, that could cause warps in the Sun's disk or indeed change the disk inclination. Indeed, the fact that the Sun's equator *is* inclined to the plane of the Solar System may be proof of the fact that the Sun did not form in isolation.

On the other hand, it can also be said that is actually quite surprising that the spin axis of the Sun and the Solar System's pole are oriented so close to parallel, *even if* the Sun was formed as an isolated object. In reality, a collapsing star forming cloud is not going to have perfect axial symmetry. Over the entire accretion time of a star, material will be falling onto the star from all different directions and with different turbulent velocities. It is actually amazing that you would end up with such a close alignment as we have in the case of the Sun.

Looking at Herbig-Haro flows from low mass stars, the large majority show an S-shaped symmetry which indicates that the late phase accretion angular momentum axis is different from the early phase angular momentum axis. So either an influence from a companion or anisotropic accretion could account for this effect.

A second question was posed about the Solar System as related to star formation. Lunar samples have revealed that heavy bombardment of the Moon's surface continued until about 7×10^8 years after the Sun formed. Is this compatible with the belief (from the decay of IR excesses) that dusty disks around young low mass stars do not survive beyond about 10^7 years? The biggest difference between dust disks and the material that was involved in the late heavy bombardment is one of scale. The material in the late heavy bombardment was confined to the inner planetary system, i.e. within a few AU from the Sun. Until we can probe the few AU scale around stars we will not be able to see how these two things are related. The other big issue is that the late heavy bombardment was a spike in the bombardment of the planets. The frequency of bombardment had dropped down to negligible levels until 3.9 million years ago when there was this extreme event, and then afterwards the bombardment rate again returned to quiescence. It is still not known for sure *what* caused this event. It is presumably due to the dynamical break up of some body within the Solar System or something moving a lot of asteroids an comets around to produce this short-lived catastrophic event.

In conclusion, we are talking about two different things in this case: dust and bodies. In light of this, 7×10^8 years is more than enough time to create all these larger bodies that bombarded the planets from the original dust disk of the Sun.

7. Binary Frequency of Star Formation

The binary frequency of stars across the stellar mass spectrum from brown dwarfs to O stars was also discussed. It appears that the companion star fraction increases with primary mass. Starting with M stars, there is a companion frequency of 40–50%, G stars have a 60% companion frequency, B stars have an even higher frequency, and with O stars the companion frequency is about 200% (meaning that O stars typically have more than one companion).

What kinds of companions are associated with the primaries? Using the spectroscopic/radial velocity survey method, no brown dwarfs have been found. Therefore a "brown dwarf" desert appears to be established for very short period binaries. To what separation ranges does the brown dwarf desert extend? Though there are some direct detections of brown dwarfs around stars in longer period orbits, there are many more non-detections than detections. One hypothesis to explain the brown dwarf desert problem is simply the effect of stellar formation by accretion. If a binary keeps accreting, this tends to push the mass ratio of the primary to secondary towards unity. So there may be a situation where we see brown dwarfs preferentially more toward lower mass, M stars.

8. Triggered Star Formation

Is *all* star formation triggered? We *do* think that triggered star formation occurs. As an example from this workshop, it appears that the M17 cluster affects its neighboring clouds and might produce secondary star formation. Furthermore in the Eagle Nebula there are "eggs" in the pillars that may be stars forming, which were triggered to form via photo-ablation and radiative implosion due to the presence of nearby OB stars.

Barring these obvious effects of stars inducing further star formation, at some level all star formation can be said to be triggered. The occurrence of star formation in any place depends on the previous history of material which caused it to be collected there: previous episodes of star formation, previous large scale dynamics of the Galaxy, or small scale turbulence within a cloud. There is always a cause. But on the other hand, all star formation can be said to be *spontaneous* because in each case it depends on its local gravity pulling material together.

So turning the question around, one could ask if all star formation is spontaneous. It seems that there is both *triggered* and *spontaneous* star formation, and the line between the two is very blurred and partly confused by semantics. It would depend on what one would consider a "trigger". Perhaps we can divide the two terms by defining each to a scale. On the *large* scale there does appear to be triggered star formation (if this is the case for *all* stars, it is not known), and on the *small* scale there is spontaneous star formation dependent only on local gravity.