Summary: Modes of Star Formation

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1. Introduction

This meeting has featured many interesting developments in a wide range of topics related to star formation, and it will not be possible for me to review all of them in this brief summary; instead, I shall focus on what seemed to me some of the main themes or conclusions of the meeting. The title "Modes of Star Formation" can refer to a variety of different aspects of star formation, and it can even mean different things to different people; we heard, for example, about 'isolated' and 'clustered' modes of star formation, 'spontaneous' and 'triggered' modes, 'quiescent' and 'starburst' modes, and even about 'low-mass' and 'high-mass' modes. Perhaps the most general type of question addressed by this subject is how star formation is organized, and what kinds of patterns we can discern in how and where it occurs.

2. Star-Forming Clouds and Cores

It has long been known that stars form in molecular clouds, and several presentations at this meeting dealt with molecular clouds and their structure and dynamics. The gross properties of these clouds, such as their sizes, masses, and linewidths, seem to have reasonably well defined values and to follow similar trends in different regions, and even in different galaxies. Molecular clouds thus exhibit some systematic properties that we might expect to be reflected in corresponding systematic features of the way in which stars form. But it is also clear on closer inspection that star formation must be a complex and even somewhat chaotic process, since molecular clouds are quite irregular in their structure and have supersonic internal turbulent motions. Progress in understanding the details of star formation has therefore been slow, and we do not yet have a theory with much predictive power.

Much effort has gone into understanding the origin and decay of the turbulence in molecular clouds, since this turbulence is the main effect counteracting gravity and since star formation cannot occur until it has been dissipated, at least locally. It has often been assumed that molecular clouds are long-lived quasi-equilibrium structures, and the apparent persistence of turbulence in them for many crossing times has been considered problematic. Magnetic fields have been thought to solve this problem by prolonging the dissipation time, but recent numerical simulations have shown that turbulence always decays within a crossing time, even with magnetic fields. The properties of molecular clouds are therefore hard to understand unless these clouds are short-lived, and indeed it

has become increasingly clear that star-forming clouds are transient structures. The ages of the young stars and clusters associated with them imply that star formation is a rapid process and continues for only about a crossing time in each region, after which the remaining gas is quickly dispersed; for example, clusters of stars older than 5 Myr have already cleared away their surrounding gas, while clusters older than 10 Myr no longer have any associated gas within many parsecs. The weak-lined T Tauri stars discussed at this meeting provide further evidence for rapid cloud dispersal, since these stars were evidently formed in situ from gas that has already disappeared after only a few Myr. If star-forming clouds are transient, there is no longer any problem in understanding why they are turbulent, since they must then be condensations in a turbulent medium that are continually forming and dispersing and that don't last long enough for their turbulence to be completely dissipated.

Various scales of structure have been distinguished in molecular gas, including features called 'clouds', 'clumps', and 'cores', which form stellar groupings of various sizes including associations, clusters, and individual stars or binary systems. Much study has been devoted to the apparently most fundamental star-forming units, the cloud cores, which are individual density peaks with relatively little internal structure. In nearby clouds, these cores have sizes of the order of 0.1 pc and masses of the order of one solar mass. Some of them contain embedded young stars, and others show evidence for infall in their line profiles which suggests that they are currently collapsing. The inferred infall motions, as we heard, are too large in both amplitude and spatial extent to be consistent with standard cloud models that assume slow quasi-static evolution, and instead they favor a more dynamical picture in which cores form and collapse rapidly into stars. Moreover, the mass spectrum of the cores in the well-studied ρ Oph cloud is quite similar to the stellar IMF, and this suggests that these cores are the direct progenitors of stars and that the stellar IMF is determined, at least in part, by the mass spectrum of the cloud cores.

3.   The Stellar IMF as a Fossil Record

Many presentations at this meeting dealt with the stellar Initial Mass Function found in different regions and systems. The apparent universality of the IMF has been emphasized in recent years, and the IMF does indeed show an impressive degree of uniformity in systems that include the local field population, nearby star-forming regions, star clusters in our Galaxy and the Magellanic Clouds, and nearby dwarf galaxies. The resulting 'standard IMF' is now fairly well defined, and it resembles the original Salpeter power law at masses above a solar mass but flattens below a solar mass and then probably declines (in logarithmic units) in the brown dwarf regime. The departure of the IMF from a power law below a solar mass is beyond question, and it appears instead that the IMF is a broadly peaked function with a characteristic mass of the order of one solar mass. This characteristic stellar mass is similar to the typical mass of the dense cores in nearby clouds, and also to the Jeans (or Bonnor-Ebert) mass predicted for cloud fragmentation at the temperatures and pressures typically observed in star-forming clouds. This suggests that the IMF is determined by cloud fragmentation processes that have a mass scale similar to the Jeans mass.

However, despite this evidence for uniformity, there is also evidence for departures from a standard IMF that is becoming increasingly difficult to ignore. For example, the Taurus region has a deficiency of brown dwarfs and possibly also of stars above a solar mass, suggesting that star formation in simple environments like the Taurus clouds produces only a limited range of masses and that stars with smaller and larger masses form only under conditions that are not present in Taurus. For example, brown dwarfs might form mostly by subfragmentation in more complex environments, while massive stars might form mostly in larger groupings or clusters. In fact, it has become increasingly clear that massive stars do form preferentially if not exclusively in clusters, and that they are most likely to form at the centers of massive and dense clusters like the Trapezium cluster. We heard about several examples of massive clusters with apparently top-heavy IMFs; for example, in the 30 Doradus cluster the IMF appears to flatten below about 2 $M_\odot$, i.e. at a somewhat higher mass than the standard IMF, while in the extremely luminous cluster M82-F the IMF may flatten below 3 or 4 $M_\odot$. The massive young Arches and Quintuplet clusters recently discovered near the Galactic center also have relatively flat IMFs, so there may indeed be a tendency for massive clusters to form preferentially massive stars.

4.   Formation of Massive Stars

The formation of massive stars has itself become a topic of major interest, and several presentations discussed the relevant observational evidence and theoretical ideas. Massive stars appear to form in exceptionally dense environments, and two competing hypotheses are that they form by gas accretion and that they form by stellar coalescence. Neither of these hypotheses can yet be excluded, and a further intermediate possibility suggested here is that interactions between dense star-forming cores are involved. In fact, such a picture seems almost unavoidable, because if one imagines that accretion is the dominant process, then the gas being accreted by the stars in a forming cluster must be very clumpy and must contain many forming stars, while if one imagines that coalescence is involved, the coalescing stars will still have massive gas envelopes that must also play a role. Thus, one is led in either case to a picture in which interactions between forming stars or protostars in dense cluster-forming cloud regions are involved. If the accumulation processes that build up massive stars are scale-free and if no new scale larger than the Jeans mass enters the problem, then a power-law upper IMF could plausibly result, but a quantitative theory of such processes is still in the future.

An extreme case of massive star formation may occur with the 'Population III' stars that form at very early times before any heavy elements have been produced. The gas temperature is then much higher than in present-day molecular clouds, and the Jeans mass is therefore also much higher. The recent simulations of early star formation presented here suggest that the first stars might have had masses between 30 and 300 solar masses. These objects would have had important consequences for ionizing and chemically enriching the early universe. Another intriguing possibility suggested here was that in the presence of a very intense radiation field, such as exists at the center of M51, the temperature and Jeans mass may again be very high, possibly allowing the formation

of isolated massive stars. The central starburst region of M82 has long been suspected to harbor a top-heavy IMF (some evidence for which may have been found in the case of M82-F), and it will be interesting to see if further studies of star formation in extreme environments reveal further examples of anomalous and possibly top-heavy IMFs.

5.   Binaries, Clusters, and Associations

The clustering of young stars on scales ranging from binaries to large associations provides another record of the way in which stars form. Like stellar masses, the properties of binaries are largely preserved from their time of formation, and this allows binary statistics to be used to infer something about the typical sites of star formation. The field population contains a mix of contributions from star-forming regions of all types, and since the frequency of binaries is observed to be lower in dense star-forming regions like the Trapezium cluster than in sparser regions like Taurus, the binary frequency in the field constrains the relative numbers of stars that could have originated in these different types of regions. A simple recipe was proposed here to account for the field population: take two parts of a 'Trapezium' population, add one part of a 'Taurus' population, and the mix reproduces quite well the binary statistics of the field. The fact that the field population resembles the Trapezium cluster more closely than the Taurus region in its binary frequency suggests that most field stars originated in clusters like the Trapezium cluster.

Infrared observations of the newly formed stars embedded in molecular clouds show that most stars do indeed form in clusters. In the Orion clouds, for example, most of the newly formed stars are located in several embedded or partly obscured clusters, of which the Trapezium cluster is just the largest. The IMFs inferred from the infrared observations of these young clusters are in good agreement with the field IMF, again consistent with the possibility that most field stars are formed in such clusters. Most of these embedded clusters must however be very short-lived, and only the largest ones can survive for any length of time as open clusters. The Trapezium cluster might evolve into something like the Pleiades cluster, probably losing most of its stars in the process, but the smaller Orion clusters will soon evaporate. Even the Pleiades cluster will not survive for long compared with the age of our Galaxy, so the oldest open clusters that we now see must be just the surviving remnants of a once much larger population. Also, we heard that in order to account for the properties of the oldest open clusters, there must once have been many clusters much more massive than those we see now, with masses of tens of thousands of solar masses. The first clusters formed in the Galactic disk might therefore have had masses more like those of globular clusters than those of present-day open clusters.

On larger scales, molecular clouds produce associations of young stars that may contain several clusters or subgroups as well as a more dispersed population that is already beginning to dissolve into the field. The classical OB associations are now known to contain not only massive stars but also many low-mass stars, and to be the birth sites of most stars of all masses. Many OB associations contain subgroups that were formed in several distinct episodes of star formation, and in some cases the most recent star formation has occurred at the edge of

an association in gas that appears to have been compressed by expanding shells produced by the earlier episodes of star formation. For example, star formation in both the ρ Ophiuchus and Orion regions is now occurring in filamentary clouds whose appearance suggests that they are being compressed and ablated by outflows from the previous centers of star formation in the region. Star formation may thus sometimes trigger further star formation in nearby gas, but the star-forming clouds are soon also destroyed by these same effects, and star formation is then shut off. Thus the feedback effects of star formation are complicated, and it may not always be clear whether the net effect is positive or negative. Generally, star formation may occur wherever large-scale gas motions cause the interstellar gas to pile up into dense molecular clouds, but the gas motions involved are often turbulent and chaotic, and it may then not be possible to identify a unique cause or triggering effect for each episode of star formation.

6.   Moving Streams as Remnants

When associations disperse, they retain some kinematic coherence because their internal motions are relatively small, and they then become moving groups or streams. The weak-lined T Tauri stars found by X-ray observations that were discussed at this meeting probably represent some of the remnants of associations that are just now dissolving into the field and becoming moving groups. Several young moving groups have been known for some time that are associated with clusters such as the alpha Perseus and Pleiades clusters, and a few older moving groups have also been identified. Most if not all of the field population probably consists of the remnants of old associations that have become moving groups, but the identification of old moving groups is difficult because they eventually form bands and not just clumps in velocity space. Therefore very complete and accurate data are needed to sort them out, but much progress should become possible with planned future instruments capable of gathering such data.

It has also become clear in recent years that the Galactic halo contains moving streams that are the debris of disrupted halo systems or satellite galaxies. A large fraction of the halo could belong to a relatively small number of streams created by the disruption of a relatively small number of satellites. Some of the nearby dwarf spheroidal galaxies have extended envelopes that are being tidally dispersed, and the debris from these systems could itself account for a significant fraction of the halo. It is also possible that most of the halo field stars could have originated in many small and relatively short-lived clusters. The recently discovered Sagittarius dwarf galaxy, which is just now being disrupted by interaction with our Galaxy, provides a clear 'smoking gun' example of a satellite that is being dispersed into an extended moving stream and thus is adding both stars and clusters to the Galactic halo. The dwarf spheroidal galaxies presently observed around our Galaxy are probably just the fading remnants of a once much more prominent system of satellites, most of which have by now merged with our Galaxy to build up the halo and perhaps also the bulge and thick disk components.

7.   The Galactic History of Star Formation

There has been much interest in reconstructing the history of star formation in our Galaxy and others from their stellar age distributions, and new results were presented here for the star formation history of our Galaxy, the Magellanic Clouds, and several other Local Group dwarfs. The non-uniform age distribution of the stars in the Galactic disk suggests that a number of episodes of enhanced star formation activity occurred at intervals of several Gyr in the past, the most recent one having occurred a few Gyr ago. It is intriguing that both the Large and the Small Magellanic Clouds also show evidence for large increases in their star formation rates at about the same time a few Gyr ago, and it has been suggested that all of these events might have been caused by a close encounter among the three galaxies a few Gyr ago. Some anomalies in the spatial distribution of gas and young stars in our Galaxy, such as the Gould Belt and other corrugations or warps, might also have been caused by recent interactions with small companions or infalling gas clouds, but the origin of these features is not yet well understood.

Additional information about the history of star formation in our Galaxy is provided by the chemical abundances of stars as a function of age. The recent results presented here confirm that, although the average metallicity of the stars in the Galactic disk has increased smoothly and monotonically with time, there is a substantial scatter in the age-metallicity relation that probably implies significant chemical inhomogeneities in the interstellar medium. The classical 'G-dwarf problem', i.e. a paucity of metal-poor stars relative to the predictions of simple models, also persists in the most recent data. Gas infall, interactions with companions, starburst events, and variability of the IMF could all play some role in explaining these observations, but galactic chemical evolution remains a poorly understood subject in all but the broadest outlines; simple models clearly fail to account for all of the observations, but the data are not yet sufficient to constrain adequately the many more complex models that have been proposed.

8.   Starbursts and Superclusters

Elsewhere in the universe, there is abundant evidence for bursts of star formation associated with interactions between galaxies, and the most extreme starbursts appear invariably to be caused by violent interactions or mergers. These interactions redistribute the gas in galaxies, typically piling it up near the center where an intense burst of star formation results. Spectacular central starbursts are especially favored if the colliding galaxies have prominent bulges, while in less centrally concentrated systems the resulting star formation activity may be more widespread. The frequency of violent interactions and starbursts increases strongly with redshift, suggesting that the earliest stages of galaxy formation and evolution might have been dominated by starbursts triggered by interactions. By contrast, star formation in most present-day galaxies is a relatively quiescent and orderly process, and interactions and triggering events now play a less important role. Present-day star formation probably results mostly from small-scale gas motions that are more random in nature and are not the result of any obvious triggering effect, although local violent events such as the forma-

tion of expanding shells by multiple supernova explosions may sometimes play a significant role in triggering local star formation.

There was much interest at this meeting in the formation of very luminous star clusters or 'superclusters'. These objects are found in regions of exceptionally vigorous star formation such as bright spiral arms, starburst regions, and galactic nuclear regions where star formation is highly concentrated. Active star formation seems generally to be highly clustered, and the fraction of stars that form in luminous clusters increases with the local star formation density in galaxies. The most luminous young clusters are of particular interest because of the possibility that they may represent young globular clusters; if they do, this would mean that the formation of globular clusters is continuing in some locations and thus is open to observational study. Some luminous young clusters are found to have the sizes and masses of globular clusters, so they could indeed be young globular clusters. However, it is not known whether they will actually survive for a Hubble time; this depends sensitively on their IMF, since survival for a long time is possible only if a cluster is sufficiently dominated by low-mass stars. If a cluster contains too many massive stars, it will lose too much mass as these stars evolve, and as a result it will soon evaporate. Even the standard IMF discussed above contains barely enough low-mass stars for a cluster to survive for a Hubble time, so it could well be that most of the luminous young clusters do not survive for a Hubble time. In this case the observed globular clusters could be, like the oldest open clusters, just the disappearing remnants of a once much larger population.

9. Star Formation in the Smallest Galaxies

Low-mass disk and irregular galaxies tend to be relatively isolated, and they lead very quiet lives, forming stars at a leisurely pace and retaining a large amount of gas. These systems may have settled into a state of marginal stability, and they may form their stars mostly in small local events wherever the self-gravity of the gas becomes sufficiently important. However, they may also be particularly vulnerable even to relatively mild interactions, which apparently can trigger galaxy-wide starbursts in them. Some dwarf galaxies such as the 'blue compact dwarfs' seem to be able to produce central starbursts without any obvious external cause, possibly as a result of a slow accumulation of gas at the center until a stability threshold is surpassed. Starbursting dwarfs of both types may account for some of the apparent excess of blue galaxies that is seen at intermediate redshifts; if so, a general conclusion might be that giant galaxies form most of their stars at large redshifts, while dwarf galaxies form most of their stars at more modest redshifts.

The Local Group dwarfs have been much studied with respect to their star formation histories, which turn out to be very diverse. The gas-poor dwarf spheroidal galaxies around the Milky Way have no young stars, yet most of them have significant intermediate-age populations indicating that they continued to form stars for many Gyr after their formation. The fraction of intermediate-age stars tends to increase with distance from the Milky Way, and the Fornax dwarf, one of the most distant ones, contains some stars younger than 1 Gyr in age. The two largest dwarf spheroidals, Sagittarius and Fornax, also have their own glob-

ular cluster systems. The star formation rates in these systems have generally decreased with time, but in some cases there have been large fluctuations or even recurring episodes of star formation separated by inactive periods. These diverse behaviors may reflect the fact that small systems are vulnerable to a number of effects that can either suppress or enhance star formation; supernova-driven gas loss and sweeping by motion through a hot ambient medium may remove gas and suppress or shut off star formation, while interactions with other systems or infall of new material may reinvigorate star formation for a brief time. But in general, rather than telling us about what drives star formation, these systems may be telling us more about how star formation sputters out when galaxies run out of gas.

10.   The Fading Fireworks

A general theme of much of this meeting has been that star formation occurs mostly in discrete events or bursts that produce stellar aggregates of all sizes ranging from small groups to galaxies. These events can have many causes, but in all cases they involve the rapid accumulation of gas in a small volume of space where self-gravity eventually overwhelms all other effects and causes rapid collapse to occur. The resulting bursts of star formation are brief but spectacular events that can produce brilliant displays of massive stars and luminous clusters. The remaining gas is then quickly dispersed, and soon the young stars and clusters are themselves mostly dispersed, creating the moving streams of which galaxies are built. Much of what astronomers study can be understood as the fossil remnants of past starburst events which were once more common than they are now. We presently see mainly the fading embers of the cosmic fireworks show, but it has left us a rich fossil record to study, and we can compare this record with the star formation activity that we can still observe in many locations. Increasingly, we can also use high-redshift observations to study directly the star formation activity that occurred at earlier stages in the evolution of galaxies, and thus check the inferences drawn from the fossil record. The evidence that is beginning to accumulate suggests that much of what happened at earlier times can be understood as scaled-up versions of the present-day star formation processes that were the main topic of this meeting.