Star Formation – An Outline

Key goals of a theory of star formation include predicting the rate of star formation and the distribution of stellar masses on the macroscopic scale, and predicting the properties of individual stars from the initial conditions on the microscopic scale. In order to answer these fundamental questions, and to understand the fascinating observed phenomenology of star-forming systems, many different processes must be understood theoretically. Over the past decade, there has been a paradigm shift from star formation in a quasistatic medium to one that occurs in a supersonically turbulent one. In addition, there have been major advances in the ability to incorporate an increasing range of physics in time-dependent numerical simulations, and vast improvements in the spatial resolution, sensitivity, and wavelength coverage of space and ground-based programs observing star-forming systems. Together, this has led to significant progress in many directions.

Based on our current understanding, the narrative of star formation contains the following elements:

- The road to star formation in a disk galaxy like the Milky Way begins when massive ($\sim 10^5 - 10^7 M_\odot$) bound structures condense gravitationally out of the diffuse ISM to create giant molecular clouds (GMCs). In the Milky Way and Local Group galaxies, GMCs have surface densities $\sim 100\ M_\odot\ \mathrm{pc}^{-2}$, independent of cloud mass or the surrounding ambient ISM conditions.

- GMCs inherit high levels of internal turbulence from the diffuse ISM. This turbulence, however, damps within a crossing time, and as yet it is not understood exactly how the highly intermittent sources of energy in the interstellar medium (including within GMCs themselves) can maintain consistency in the observed level of turbulence in GMCs.

- The turbulence within GMCs is highly supersonic and approximately Alfvenic. Magnetized turbulence combines with self-gravity to cause fragmentation of clouds into a hierarchy of clumps and filaments. Turbulence also imposes a log-normal distribution of densities.

- Spatially-defined structures within GMCs tend to have internal velocity dispersions that increase with size as $\sigma \propto \ell^{0.5}$, which is understood to reflect the underlying power spectrum scaling expected for supersonic turbulence. Intermediate-scale, moderate-density structures are not gravitationally bound and are transient.

- Some of the densest regions created by turbulence become self-gravitating cores with masses that are typically of order the Bonnor-Ebert mass. Low mass cores have subsonic internal turbulent velocities, consistent with expectations for formation in post-shock regions. The distribution of core masses appears to be similar to the initial mass function (IMF) for stars, and the rate of core formation can be estimated based on the turbulent properties of a GMC.

- Cores are seen to develop inside filamentary structures within GMCs and are frequently clustered, due to the dominance of large scales in the turbulent flow. Forming cores sample from the local vorticity of the turbulence to determine their spins.

- Dense cores that begin or become (through ambipolar diffusion) magnetically supercritical undergo self-gravitating collapse, first becoming strongly stratified internally (outside-in), and then undergoing envelope infall (inside-out). Accretion rates decline over time. Observations show that magnetic fields in cores are roughly critical, and this is consistent with inferred core lifetimes.

- Continued Bondi-Hoyle accretion can occur from the surrounding ambient medium after the collapse and infall of the initial self-gravitating core, but it is not yet known how much this can increase the masses of stars, given the turbulent, evolving conditions in star-forming environments.

- The collapse of a core leads to the formation of a rotating disk interior to an accretion shock; significant magnetic flux is lost in this collapse process, although not enough to account for the small fluxes observed in stars. Magnetic braking affects the formation of disks, particularly at early stages.

- Disks accrete due to a combination of processes that transport angular momentum outward; these transport mechanisms include gravitational stresses when the surface density is high enough, and magnetic stresses when the ionization is high enough. Differing accretion rates at adjoining radii may lead to mass build-up and then outbursts, observable as FU Orionis-type events.

- Powerful winds are magnetocentrifugally driven from the surface of circumstellar disks at a range of radii. The inner portion of the wind, which arises nearest the central star, becomes collimated into a jet-like flow due to magnetic hoop stresses.

- The impact of a wide-angle, stratified disk wind on the protostellar core sweeps up much of the ambient gas into a massive molecular outflow. This reduces the net efficiency of star formation to $\sim 1/3$. The combined action of many outflows also helps to energize dense, star-cluster-forming clumps.

- The material in circumstellar disks is lost by a combination of inward accretion, mass loss in winds, and photoevaporation (starting with gap opening in the central region). Observed mean disk half-lifes are $\sim$ 2Myr, and the final clearing appears to be spatially correlated across all radii.

- Observed disk lifetimes place limits on planet formation models. Growth of solids from dust to planetesimals to planets involves several stages, with gas-solid interactions particularly important at the earliest stages. Migration due to aerodynamic drag (for small bodies) and gravitational torques (for large bodies) also places strong constraints, and collective effects may be required to cross the “meter-size” barrier.

- Massive stars form from cores that are considerably more massive than a Bonnor-Ebert mass, and are most likely highly turbulent. Radiation pressure strongly affects the dynamics of massive star formation, but can be overcome by the combined action of disk formation, protostellar outflows and radiation-hydrodynamic instabilities in the accreting gas. It is not clear whether protostellar feedback determines the maximum mass of the stars that form.

- Massive, luminous stars ionize their surroundings into HII regions. The expansion of these regions into ambient gas at ~ 10 km s^{-1} energizes GMCs, contributing to the large-scale turbulent power. However, this process is difficult to regulate, and can unbind GMCs within a few dynamical crossing times. By the time they are finally destroyed, GMCs may have lost much of their original mass by photoevaporation.

- The destruction of GMCs returns almost all of the gas they contain to the diffuse phase of the ISM, with a mean star formation efficiency over the cloud lifetime of $\sim 1 - 5\%$. This low efficiency can be understood as a consequence of the small fraction of mass that is compressed into clumps dense enough that turbulence does not destroy them before they collapse, combined with cloud lifetimes of only a few large-scale crossing times.

- The return of GMC gas to the diffuse ISM completes the cycle of star formation, which then begins anew.

The coming decade will test and revise this narrative of star formation, particularly with the advent of ALMA and the continued advances in numerical simulation. Turning this narrative into a quantitative, predictive theory will provide a foundation for addressing many of the outstanding questions in astrophysics today, ranging from the formation of planets to the evolution of galaxies and the origin of the elements.