Star Formation in the Milky Way

Hubble Science Briefing
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STScI

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Star Formation in the Milky Way…

• First, a bit of history…
• Formation of Sun-like stars - in isolation
• Star formation in the cluster environment
• Low and High Mass stars
• The Impact of the Hubble Space Telescope
• Star Formation Science with JWST
History - The Discovery of the “T Tauri Stars”

The Original 11 (Joy, 1945)
- Stars that show irregular flux variations
- Stellar absorption features typical of sun-like stars
- Often associated with bright/dark nebular regions
- Curious Emission Line spectra
The Discovery of the “T Tauri Stars”

A few years later (1949) Armenian Astronomer V. Ambartsumian first postulated that these “T Tauri variables” are in-fact sun-like stars in the very early stages of formation. Thus, the science of star formation had begun!
Shortly after the “T Tauri Stars” were introduced…

“variable stars of Orion Type”

and variable “Ae/Be stars” (Herbig 1950’s)

Seen to be concentrated around the Orion nebula cluster

The variables of “Orion Type” were very similar to the T Tauris
The Orion Nebula Cluster (M42)

- M42 gave astronomers some much-needed clues into the formation of stars
- G. Herbig (1952) and other astronomers of the time noted that the Orion cluster has several hot, massive stars - \( \theta^1 \) Ori C is an O6 star, \(~40\) solar masses!
- Such massive stars consume their nuclear fuel extremely quickly, and so do not live very long lives.
- Astronomers in the 1950’s realized that these massive stars must be very young, and probably formed out of these swirling clouds of gas and dust.
The Orion Nebula Cluster - A stellar Nursery!

- Astronomers identified that the massive stars in the nebulae likely formed out of the gas and dust from the molecular clouds here.
- Are other, lower mass stars in the region also young?
- How did these stars form in this complex environment…?
Sign Posts of Star Formation

Massive stars forming in a dense molecular cloud emit energy that ionizes the surrounding gas - producing HII regions!

The atomic elements present in the gas emit at characteristic wavelengths, (Hydrogen, Oxygen, Nitrogen, Sulphur, Iron, etc...) & these gases create the glowing clouds of material seen in images

The Omega Nebula (M17)

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Tracy Beck - HSB
Older areas and Regions of Lower mass star formation - with no hot stars that ionize nearby gas - can be traced by dark nebula from low mass, quiescent clouds, or sometimes by light scattered off of nearby cloud material (e.g., the T Tauris!)
Star Formation is Happening Throughout the Milky Way!

- Milky Way
- M16 (Eagle)
- M17 (Horseshoe)
- Hale-Bopp
- M8 (Lagoon)
- Jupiter

Zoom-in
size of our solar system
The Formation of Sun-like stars

Stars form in a range of environments…

• From Giant molecular clouds

  \[ M \sim 10^6 \, M_{\text{sun}}, \quad R \sim 10 \, \text{pc} \]

  = Star clusters with massive O & B type stars! (Like Orion, M16)

• To low density molecular core regions

  \[ M \sim 10^4 \, M_{\text{sun}}, \quad R \sim 0.1 \, \text{pc} \]

  = A few stars, & with few or no high mass (Taurus SFR)
Formation of Sun-Like Stars - In Isolation
(Like in the sparse regions of the Taurus SFR)

M. Hogerheijde 1998, after Shu et al. 1987
Molecular clouds have clumpy structures, “dark cloud cores” from which stellar embryos take shape.

“dark cloud cores” are seen with deep, sensitive infrared exposures that can peer through the clouds, and at radio wavelengths where the cloud material emits.
Formation of Sun-Like Stars - In Isolation

When the conditions are right, these dark cloud cores contract due to gravity to form a proto-star

- What causes a cloud core to collapse?
- Let’s consider the forces acting on a cloud:
  - Gravity = acts to collapse the cloud
  - Internal Thermal Pressure = supports against collapse
- In perfect hydrostatic equilibrium, gravity and pressure balance exactly.
- In order for a cloud to collapse to a star, the gravity must overcome the internal gas pressure...
Formation of Sun-Like Stars - In Isolation

- For a given cloud of Temperature $T$ and density $\rho$, there is a critical mass for which gravity will dominate the internal pressure and the cloud will collapse...

$$M_J \propto T^{3/2} \rho^{-1/2}$$

**The Jeans Mass**

- The Jeans Mass is a fundamental quantity in star formation science...

When the conditions are right, one of these dark cloud cores contracts due to gravity to form a proto-star

If cloud Temperature increases - cloud pressure increases and the Jeans mass is larger

If cloud density increases - cloud’s gravity is higher and the Jeans mass is smaller
Formation of Sun-Like Stars - In Isolation

**The Jeans Mass**

\[ M_J \propto T^{3/2} \rho^{-1/2} \]

& Observations of dark, quiescent clouds have shown that:

\[ \rho \sim 10^{-19}\text{g/cm}^3 \] in dark cloud cores.

\[ T \sim 10\text{K} \] in dark cloud cores.

So:

\[ M_J \sim 7.6 \times 10^{32} \text{ g} \sim 0.4M_{\odot} \]

The Jeans Mass is the minimum mass that a dark cloud should have to collapse on its own from self-gravity dominating internal pressure.
The Formation of Sun-Like Stars - In Isolation

What happens when a Cloud starts collapsing?

• *Initially:* The gas can cool very efficiently by emission from molecules such as CO (seen in radio).
• So, collapse is *Isothermal* (T constant) during the early phases. Gravity becomes even more dominant over pressure, & \( M_J \) drops
• This allows for the possibility that the cloud might fragment into smaller sub-clouds during the collapse process

\[ M_J \sim 7.6 \times 10^{32} \text{ g} \sim 0.4M_{\text{sun}} \]

Theory has a difficult time explaining very low mass stars forming in isolation—cloud fragmentation during collapse!?
The Formation of Sun-Like Stars - In Isolation

- As the young star collapses, the tiny slightest bit of initial angular momentum is conserved in the system, and the rotating cloud becomes a rotating, flattened disk.
- Extended material in the remnant formation cloud (the envelope) is accreted onto the disk.
- Material in the rotating disk is accreted onto the central star, & the star builds up its mass.
Formation of Sun-Like Stars - In Isolation

- Circumstellar material is accreted onto the central star.

- The accretion process is sometimes eruptive or episodic - FU Ori, EXOr outbursts, where mass is at once accreted onto the star in large quantities.

- The process of disk material accreting onto the central star is not 100% efficient...

Artists conception of a protostar
Formation of Sun-Like Stars - In Isolation

- The process of disk material accreting onto the central star is not 100% efficient.

- Through processes not yet understood, some of the material being accreted onto a young star is ejected out through the poles of the system in spectacular protostellar outflows of material!
Formation of Sun-Like Stars - In Isolation

HST Image of a circumstellar disk seen in silhouette with a powerful outflow

While some aren’t?

HST Image of a powerful outflow from a young protostar still embedded within its natal cloud

Why are some outflows well collimated?
In the latter stages of the star formation process, the remnant cloud material is gone, the outflows have ceased. The circumstellar disk material is accreted onto the central star or it coalesces into planets, comets, asteroids…etc…
But… Not all stars form in “Isolation”!? 

It’s True! 80-90% of stars form in clusters! Not ‘in isolation’ like the sparse cloud regions of Taurus (Lada et al. 1991, Lada & Lada 2002).

In general, observations suggest that young, sun-like stars form in similar manners where ever they are. BUT - there are some important differences…

Orion Cluster
Not all stars form in “Isolation”!

There are some important differences!

But the massive stars could help push gravity in its dominance over cloud pressure - i.e., nearby supernova explosions. $M_{\text{Jeans}}$ could go down to external effects (“triggering” SF)

Interactions with cluster members can affect a forming star’s disk, (disk truncation) and may alter the planets that ultimately form there.
In the latter stages of the star formation process, the remnant cloud material is gone, the outflows have ceased. The circumstellar disk material is accreted onto the central star or it coalesces into planets, comets, asteroids…etc…
What about stars that aren’t “Sun-Like”?

Deep infrared images of star clusters reveal extremely low mass members, including “brown dwarfs” (failed stars).

Some of the lowest mass objects are just a few Jupiter masses! Dubbed “free-floating planets” (Lucas et al. 2000)

With masses $<< M_{\text{Jeans}}$, How do these objects form?

Theories for their origin largely center on formation with more massive stars - fragmentation of the collapsing cloud and ejection of the lowest mass objects from the system

An Infrared View of the Orion Cluster
What about stars that aren’t “Sun-Like”?

Some great animations of star formation:
http://www.astro.ex.ac.uk/people/mbate/Cluster/index.html

M. Bate et al. (2002 - 2007, 2008)

These simulated animations show an initial cloud at $T=0$ evolving over ~250,000 years to collapse and fragment form a small cluster of ~1200 stars. Some of the low mass members are formed in the inner cloud regions and ejected into outer regions of the cluster.

Theoretical simulations CAN explain the existence of the “free floating planets”
Also - What About High Mass Stars?
Those 20+ $M_{\text{sun}}$ Stars that Linger out there?

The formation of massive stars - especially of extremely massive 10+ $M_{\text{sun}}$ stars - is one of the greatest challenges in modern astrophysics.

The canonical model for sun-like stars shouldn’t work, in theory. High mass stars - don’t live long!

They must begin burning nuclear fuel while still accreting mass = strong radiation pressure = disruption and dispersal of circumstellar disk material.

HST Image of the Pistol Star
At ~100+ solar masses, this is one of the most massive stars known in the milky way.
Also - What About High Mass Stars?
Those 20+ $M_{\text{sun}}$ Stars that Linger out there?

- The canonical model for sun-like stars shouldn’t work, in theory
- The strong radiation from the forming star - pushes against accreting mass, disrupts the disk and disperses the forming cloud material before it can all accrete.

HST Image of the Eta Carina
At ~100-150 solar masses, this is another of the most massive stars known in the milky way
Also - What About High Mass Stars?

Strong radiation - pushes against accreting mass…

HOWEVER… recent observations that can pierce through the dense dust and gas reveal powerful and extensive outflows from forming high mass stars.

The cavities cleared by the powerful outflows allow radiation to escape out the poles!

Only extremely recent observations in the last several years have confirmed the presence of circumstellar disks around massive stars!

Massive stars do seem to form in a similar manner to low mass stars!

Image of the Young, Massive star AFGL 2591

Massive stars have extremely strong outflows!
One More Complication for the Star Formation Picture…

Studies of the Milky Way have shown that 50-60% of stars form in binary systems, or higher order multiples! (triples, quadruples, etc…)

Alberio (β Cyg) - a visual binary and observing lab favorite!

High mass stars often have more companions - the multiplicity of high mass stars is nearly 100%, and many are in high order systems.
Stars often Form as Binaries or Higher order Multiples!...

An image of scattered light off material around the GG Tau system (~40AU separation) - shows a “ring” of material surrounding the stars. Though - full system is not shown, GG Tau is a quadruple star!

- Nearby companion stars can affect the normal evolution of circumstellar disks - theory shows that disks are truncated at 1/3 of the separation of the companion. This affects the planet formation process!
- As shown above, binary stars can have circum-binary disks! Can planets form in these circumbinary rings??
Stars often Form as Binaries or Higher order Multiples!

Hollywood’s view of Planet formation around Binary stars…

Can planets form in circumbinary rings??
HST Image of the Carina Nebula
HST Image of the Carina Nebula

Eta Carina - 100 to 150Msun!
Pillars of gas and dust within the Carina nebula

Dense cloudlets where young stars are forming are seen, as are regions of the cloud that have eroded from the radiation pressure from nearby hot stars.

Jets and outflows are also seen.
In Star Formation Science, What will JWST See?

JWST will be extremely sensitive - many of our “favorite” stars and SFRs are too bright!

We have to go FAINTER!!
• Lower mass stars & brown dwarfs
• Younger, more obscured proto-stars
• Young stars that are forming in more distant regions!

Scheduled for Launch in 2014, JWST will peer at star forming regions at Infrared wavelengths
In Star Formation Science, What will JWST See?

JWST’s Infrared Wavelengths can pierce through the gas and dust that young stars form in to see the stellar embryos in the very early stages of mass accumulation.

Can we see the very young protostars in the earliest stages of formation?
JWST Will have better sensitivity and resolution than the Spitzer Space Telescope, and will be able to spatially resolve dust disks around forming stars with exquisite detail!
Star Formation in the Milky Way!

- Some of the most spectacular views of our galaxy come from star formation science!
- Reviewed the Formation of sun-like stars, low / high mass stars, multiplicity and the future, with JWST…
- Still many open questions:
  - How does mass accretion onto a protostar turn into outflow?
  - How do the lowest mass stars/brown dwarfs form?
  - How does multiplicity affect the formation of stars and their planets?