Stars are the fundamental objects of the cosmos
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- They transform hydrogen, the primary product of the big bang, into the heavy elements of the periodic table.
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- Through stellar evolution they control evolution of all stellar systems including clusters and galaxies.
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- They transform hydrogen, the primary product of the big bang, into the heavy elements of the periodic table.

- Through stellar evolution they control evolution of all stellar systems including clusters and galaxies.

- They provide the sites for planetary systems and the energy necessary for development of life.
A Little History.....
And God made two great lights; the greater light to rule the day and the lesser light to rule the night: he made the stars also.

And God set them in the firmament of the heaven to give light upon the earth.
Aristotle’s Universe  (384 BC – 165 AD)
Greeks Invent The Scientific Cosmos

There are two realms of the Universe:

the perfect heavens
and
the imperfect earth.
Aristotle’s Universe (384 BC – 165 AD)
Greeks Invent The Scientific Cosmos

There are two realms of the Universe:

the perfect heavens
and
the imperfect earth.

Stars consist of *aether*, a perfect, unchanging substance.
Copernicus 1473-1543

NATIONAL COPEFRONCI

net, in quo terram cum orbe lunari tanquam epicyclo contineri diximus, Quinto loco Venus nono mensae reductur, Sextum denique locum Mercurius teneat, octauaginta dieorum spacio circu- currente, in medio uero omnium resideret Sol. Quis enim in hoc

[Diagram of the Copernican heliocentric model]

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Suntur secum deum, XXX. revisi...
Problem: no stellar parallax!

Tycho Brahe 1546 - 1601
Solution: stars are very distant (and very luminous)!
“First it is allowed, as I have endeavoured to shew, by all modern Philosophers, that the Sun and the Stars are all of the same or like Nature; consequently, that the Stars are all Suns, and that the Sun himself is a Star”

Thomas Wright in “An Original Theory of The Universe”, 1750
But what ‘s the Sun?
“But if the matter was evenly diffused through an infinite space, it would never convene into one mass but some of it convene into one mass & some into another so as to make an infinite number of great masses scattered at great distances from one another throughout all the infinite space. And thus might the Sun and Fixt stars be formed supposing the matter were of a lucid nature.”

Newton to Rev. Richard Bentley, 10 December 1692
“In my paper of observations of the nebulous part of the heavens, I have endeavored to shew the probability of a very gradual conversion of the nebulous matter into the sidereal appearance.”

William Herschel and The Concept of Cosmic Evolution

“but… why should we not look up to the universal gravitation of matter as the cause of every condensation, accumulation, compression and concentration of the nebulous matter?

Star Formation is an ongoing process!
As such it is subject to direct empirical study.

William Herschel and The Concept of Cosmic Evolution

Protoplanetary Disks: A slight digression

Kant-Laplace Nebular Hypothesis

A nebula in slow rotation, gradually pulled together by its own gravitational force and flattened into a spinning disk, gave birth to the Sun and planets.
“The riddle of nebulae was solved. The answer which had come to us in the light itself read: Not an aggregation of stars, but luminous gas…the light of this nebula had been emitted by a luminous gas.”

The New Astronomy of the Nineteenth Century, June, 1897
“The riddle of nebulae was solved. The answer which had come to us in the light itself read: Not an aggregation of stars, but luminous gas…the light of this nebula had been emitted by a luminous gas.”

But the composition of these luminous fluids, being composed of hydrogen and nitrogen, differed from stars and planets and could not be the material from which stars formed as Herschel had suggested!

William Huggins
1824 - 1910

The New Astronomy of the Nineteenth Century, June, 1897
“The riddle of nebulae was solved. The answer which had come to us in the light itself read: Not an aggregation of stars, but luminous gas...the light of this nebula had been emitted by a luminous gas.”

The New Astronomy of the Nineteenth Century, June, 1897

“The conclusion is strongly indicated that the order of the abundance of the elements in the solar atmosphere is much the same as in the earth’s crust.”

Setting the Stage: Discovery of The Composition of Stars


C. Payne-Gaposchkin
1900-1980

Two fundamental results:

1- Stars have uniform composition and
2- Stars are primarily made up of hydrogen

“It is the best doctoral thesis I have ever read” H.R. Russell

“undoubtedly the most brilliant PhD thesis ever written in astronomy” O. Struve
In 1938 Stromgren showed that stellar interiors composed of primarily hydrogen would have central temperatures \( \sim 10^7 \) K much lower than if they were made of iron.

In 1938 Bethe showed that with such central temperatures fusion reactions (CNO and p-p cycles) could power stars and thus demonstrated that:

Stars are thermo-nuclear reactors which fuse the primary product of the big bang into heavier elements of the periodic table releasing enormous amounts of energy in the process.
Fig. 4—Color-magnitude diagram of NGC 2264. Dots represent photographic, and circles photometric, observations. Vertical lines indicate known light variables; horizontal lines indicate stars having Ub - V \( \approx 0 \). Small symbols indicate observations of lower weight. Observed values of the magnitudes and colors have been plotted. The lines represent the standard main sequence and giant branch of Johnson and Morgan (1953), corrected for the uniform reddening of the cluster.
STUDIES OF EXTREMELY YOUNG CLUSTERS. I. NGC 2264

Merle F. Walker*
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
Received May 21, 1956

ABSTRACT

Three-color photoelectric and photographic observations of NGC 2264 have been obtained to \( V = 17 \), in order to investigate the color-magnitude diagram of an extremely young cluster of stars. The diagram indicates that the cluster possesses a normal main sequence extending from O7 to A0, below which the stars fall above the main sequence. The reality of this effect has been confirmed by spectroscopic observations. The shape of the color-magnitude diagram agrees approximately with that predicted theoretically for clusters which are so young that the fainter stars are still in the process of contracting gravitationally from the prestellar medium and have not yet reached the main sequence. The age of the cluster given by the point where the cluster stars depart from the main sequence is about \( 3 \times 10^6 \) years.
Herschel was Right!

Star Formation is an ongoing process!
And is subject to direct empirical study.

William Herschel
1738-1822
The Unsolved Problem of Star Formation:
Setting the Boundary and Initial Conditions
BOUNDARY CONDITIONS
BOUNDARY CONDITIONS

Compositions, Luminosities, Temperatures, Sizes, & Masses
BOUNDARY CONDITIONS

Luminosities, Temperatures, Sizes, & Masses
BOUNDARY CONDITIONS

Masses
BOUNDARY CONDITIONS

Mass
Once formed, the entire life history of a star is essentially predetermined by a single parameter: the star’s initial mass.
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The IMF (the frequency distribution of stellar masses at birth) plays a pivotal role in the evolution of all stellar systems from clusters to galaxies.
Once formed, the entire life history of a star is essentially predetermined by a single parameter: the star’s initial mass.

The IMF (the frequency distribution of stellar masses at birth) plays a pivotal role in the evolution of all stellar systems from clusters to galaxies.
1- The Initial Mass Function (IMF)

Muench et al. 2002
1- The Initial Mass Function (IMF)

Muench et al. 2002

The graph shows the distribution of masses in solar masses with logarithmic counts on the y-axis. The completeness limit is indicated by a vertical line.
Fundamental Boundary Conditions

1- The Initial Mass Function (IMF)

The IMF exhibits a broad peak between 0.6 and 0.1 $M_{\odot}$ suggesting a characteristic mass associated with the star formation process.
The IMF exhibits a broad peak between 0.6 and 0.1 $M_\odot$ suggesting a characteristic mass associated with the star formation process.

Larson (2005; MNRAS 359, 211.)

This is perhaps the most fundamental fact concerning star formation that needs to be explained by any theory; some feature of the physics of star formation must yield a characteristic stellar mass that is a little less than one solar mass.
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2- Stellar Multiplicity

![Graph showing Single Star Fraction vs Spectral Type]

Lada 2006
Fundamental Boundary Conditions

2- Stellar Multiplicity

![Graph showing the relationship between single star fraction and spectral type.](image)

Lada 2006
2- Stellar Multiplicity

Multiplicity is a function of stellar mass

Lada 2006
2- Stellar Multiplicity

Multiplicity is a function of stellar mass

Most (~70%) stars are single!
Fundamental Boundary Conditions

2b- Primordial Stellar Clustering

Grasdalen, Strom and Strom 1974
Fundamental Boundary Conditions

2b- Primordial Stellar Clustering

E. Lada, Depoy, Evans & Gatley 1991
Fundamental Boundary Conditions

2b- Primordial Stellar Clustering

KPNO 50 inch

E. Lada, Depoy, Evans & Gatley 1991
2b- Primordial Stellar Clustering

E. Lada, Depoy, Evans & Gatley 1991
Fundamental Boundary Conditions

2b- Primordial Stellar Clustering

E. Lada, Depoy, Evans & Gatley 1991
Spitzer survey
Megeath et al. 2010
Fundamental Boundary Conditions

2b- Primordial Stellar Clustering

E. Lada, Depoy, Evans & Gatley 1991
INITIAL CONDITIONS
Initial Conditions
Initial Conditions

E. Lada 1991

Dense Gas
Star formation confined to relatively dense ($>10^4$ cm$^{-3}$) gas ($A_V > 10$ mag).

Initial Conditions
Initial Conditions

Stars form in Dense, Dark Cloud Cores

Initial Conditions = Basic physical properties of starless cores:

mass, size, temperature density, pressure, kinematics
Initial Conditions
The Pipe Nebula
The Pipe Nebula
The Pipe Nebula

Result: 18 YSOs!!
Result: 18 YSOs!!
Overall star formation activity is insignificant, confined to 0.1% of the total gaseous mass.
Distribution of core masses (139 cores)

Alves, Lombardi, Lada 2007; Rathborne et al. 2008
Distribution of core masses (139 cores)

Alves, Lombardi, Lada 2007; Rathborne et al. 2008
Distribution of core masses (139 cores)

Alves, Lombardi, Lada 2007; Rathborne et al. 2008
Distribution of core masses (139 cores)

STARS

Alves, Lombardi, Lada 2007; Rathborne et al. 2008
Distribution of core masses (139 cores)

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Alves, Lombardi, Lada 2007; Rathborne et al. 2008
Distribution of core masses (139 cores)

Star Formation Efficiency is the Key

Alves, Lombardi, Lada 2007; Rathborne et al. 2008
Mean Core Densities

Frequency Distribution of Core Densities

Pipe Cores

Number

Density (cm$^3$)
Mean Core Densities

Median Core Density = 10,000 cm$^{-3}$
Mean Core Densities

Frequency Distribution of Core Densities

Median Core Density = 10,000 cm$^{-3}$
Molecular Line Survey
Core to Core Velocity Dispersion ($^{18}$O):

Muench et al. 2007
Core to Core Velocity Dispersion ($^{18}$O):

$$\sigma_{pipe} = 0.26 - 0.28 \text{ km/s}$$

Muench et al. 2007
Dense cores are thermally supported!

Ratio Thermal to Non-Thermal Pressures

Thermal Regime

Non-Thermal Regime

Core Mass ($M_\odot$)
Dense cores are thermally supported!

“Thermal pressure is thus a final irreducible barrier to star formation that remains even after turbulence and magnetic fields have been dissipated.” Larson (2005)
$P_{\text{total}} = P_{\text{thermal}} + P_{\text{NT}}$
Pressure Confinement of Pipe Cores

\[ P_{\text{total}} = P_{\text{thermal}} + P_{\text{NT}} \]
Pressure Confinement of Pipe Cores

\[ P_{\text{total}} = P_{\text{thermal}} + P_{\text{NT}} \]
$P_{\text{total}} = P_{\text{thermal}} + P_{\text{NT}}$
Pressure Confinement of Pipe Cores

\[ P_{\text{total}} = P_{\text{thermal}} + P_{\text{NT}} \]

\[ P \approx \pi G \Sigma^2 \]

ISM
Pressure Confinement of Pipe Cores

\[ P \approx \pi G \Sigma^2 \]

\[ P_{\text{total}} = P_{\text{thermal}} + P_{\text{NT}} \]
B 68: Radial Density Profile

\[ \xi_{\text{max}} = 6.9 \pm 0.2 \]

Critical Bonnor-Ebert Sphere
Core structure is set by the requirement of pressure equilibrium with external medium!
On the Origin of the Core and Stellar Masses
Stability of Pipe Cores

$M/W_{BE}$ vs Core Mass ($M_\odot$)

Non-equilibrium

Equilibrium
Stability of Pipe Cores

\[ M_{BE} = 1.82 \, (n_4)^{-0.5} \, (T_{10})^{1.5} \quad (\text{solar masses}) \]
Stability of Pipe Cores

\[ \frac{M}{M_{BE}} \]

Core Mass \((M_\odot)\)

Non-equilibrium

Equilibrium
Stability of Pipe Cores

Non-equilibrium

Equilibrium
The BE Critical Mass corresponds approximately to the characteristic mass of the core mass function!
Origin of Cores: Jeans (thermal) Fragmentation in a Pressurized Medium

Stability of Pipe Cores

Non-equilibrium

Equilibrium
Nearest Neighbors
Nearest Neighbors

Median separation = 0.26 pc

Pipe Nebula Cores
Nearest Neighbors

\[ \lambda_{\text{Jeans}} = c_s \left( \frac{\pi}{G \rho} \right)^{1/2} = 0.2 \left[ T_{10} \right]^{1/2} \left[ n_4 \right]^{-1/2} \text{ pc} \]

Median separation = 0.26 pc

Pipe Nebula Cores
Nearest Neighbors

Thermal (Jeans) Fragmentation!

\[ \lambda_{\text{Jeans}} = c_s (\pi / G \rho)^{1/2} = 0.2 \left[ T_{\text{10}} \right]^{1/2} \left[ n_4 \right]^{-1/2} \text{ pc} \]
Nearest Neighbors

\[ \lambda_{\text{Jeans}} = c_s \left( \frac{\pi}{G \rho} \right)^{1/2} = 0.2 \left[ T_{10} \right]^{1/2} \left[ n_4 \right]^{-1/2} \text{ pc} \]

Median separation = 0.26 pc

Thermal (Jeans) Fragmentation!

“The Jeans scale must therefore play a key role in at least the final stages of star formation process regardless of what happens during earlier evolution of star-forming clouds.” Larson (2005)
On the ORIGIN OF THE CMF/IMF:
On the ORIGIN OF THE CMF/IMF:

A process of thermal-Jeans fragmentation?
On the ORIGIN OF THE CMF/IMF:

\[ \text{CMF} \{ \log m \} = c_1 \psi(\log\{m/m_0\}, s_i); \]
On the ORIGIN OF THE CMF/IMF:

\[ \text{CMF}(\log m) = c_1 \psi(\log \frac{m}{m_0}, s_i); \quad m_0 = m_{\text{BE}}^{**} \]

**\(m_{\text{BE}} = \text{Constant} \times a^4 (P_{\text{surface}})^{-0.5}\)  

Bonnor-Ebert Mass Scale
On the ORIGIN OF THE CMF/IMF:

\[ \text{CMF} \{ \log m \} = c_1 \psi(\log \{m/m_0\}, s_i); \quad m_0 = m_{BE}^{**} \]

\[ \text{IMF} \{ \log m \} = c_2 \psi(\log \{m/m_c\}, s_k); \]

**\( m_{BE} = \text{Constant} \times a^4 \left( P_{\text{surface}} \right)^{-0.5} \) **

Bonnor-Ebert Mass Scale
On the ORIGIN OF THE CMF/IMF:

\[
\text{CMF}\{\log m\} = c_1 \psi(\log\{m/m_0\}, s_i); \quad m_0 = m_{\text{BE}}^{**}
\]

\[
\text{IMF}\{\log m\} = c_2 \psi(\log\{m/m_c\}, s_k); \quad m_c = \text{SFE} \: m_{\text{BE}}
\]

**\(m_{\text{BE}} = \text{Constant} \times a^4 \left(P_{\text{surface}}\right)^{-0.5} \)**

Bonnor-Ebert Mass Scale
The Star Formation Rate: Scaling the IMF
The Star Formation Rate: Scaling the IMF

$$\text{IMF}\{\log m\} = c_2 \ \psi(\log\{m/m_c\}, \ s_k); \ m_c = SFE \ m_{BE}$$
The Star Formation Rate: Scaling the IMF

$$\text{IMF} \{ \log m \} = c_2 \psi(\log\{m/m_c\}, s_k); \quad m_c = SFE \ m_{BE}$$

Yield = SFR $\times$ $\Delta t$
The Star Formation Rate: Scaling the IMF

$$\text{IMF}\{\log m\} = c_2 \psi(\log\{m/m_c\}, s_k); \quad m_c = \text{SFE} \ m_{\text{BE}}$$
The California Molecular Cloud

Comparing the California and Orion Molecular Clouds
Comparing the California and Orion Molecular Clouds

The two clouds are nearly identical in mass & size
Comparing the California and Orion Molecular Clouds

The two clouds are nearly identical in mass & size

YSOs(Orion) > 10 x YSOs(California)

SFR(Orion) > 10 x SFR(California)
Comparing the California and Orion Molecular Clouds

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SFR(Orion) > 10 x SFR(California)
Comparing the California and Orion Molecular Clouds

The two clouds are nearly identical in mass & size

OMC has 10 x as much material at $A_V > 10$ mag as the CMC

YSOs(Orion) $> 10 \times$ YSOs(California)

SFR(Orion) $> 10 \times$ SFR(California)
Comparing the California and Orion Molecular Clouds

The two clouds are nearly identical in mass & size

OMC has 10 x as much material at $A_V > 10$ mag as the CMC

YSOs(Orion) > 10 x YSOs(California)

$SFR(Orion) > 10 \times SFR(California)$

$OMC$ has 10 x as much material at $A_V > 10$ mag as the CMC

Or 10 x as much gas at $n(H_2) > 10^4 \text{ cm}^{-3}$ than CMC
Comparing the California and Orion Molecular Clouds

The two clouds are nearly identical in mass & size

OMC has 10 x as much material at $A_V > 10$ mag as the CMC

Or 10 x as much gas at $n(H_2) > 10^4$ cm$^{-3}$ than CMC

YSOs(Orion) > 10 x YSOs(California)

SFR(Orion) > 10 x SFR(California)
What determines the Star Formation Rate?

In external galaxies global star formation rate correlates directly with amount of dense gas.
What determines the Star Formation Rate?

\[ \text{SFR} \sim M_{DG} \]

In external galaxies global star formation rate correlates directly with amount of dense gas

Gao & Solomon 2004
What determines the Star Formation Rate?

\[ \text{SFR} \sim M_{DG} \]

In external galaxies global star formation rate correlates directly with amount of dense gas.
What determines the Star Formation Rate?

$\text{SFR} \sim M_{DG}$

Wu et al. 2005

Galaxies

Milky Way

Wu et al. 2005
What determines the Star Formation Rate?

$$\text{SFR} \sim M_{DG}$$
What determines the Star Formation Rate?

\[ \text{SFR} \sim M_{DG} \]

\[ \text{SFR} = \varepsilon_{SF} \frac{M_{DG}}{\tau_{SF}} \]

---

Galaxies

Milky Way

Wu et al. 2005
What determines the Star Formation Rate?

\[ \text{SFR} \sim M_{DG} \]

\[ \text{SFR} = \varepsilon_{SF} M_{DG} / \tau_{SF} \]

\textbf{If:} \quad \text{SFR} \sim M_{DG}

\textbf{If:} \quad \text{SFR} \sim M_{DG}

\text{Galaxies}

\[ Y = 1.01X + 2.85 \]

\text{Milky Way}

\text{Wu et al. 2005}
What determines the Star Formation Rate?

\[ \text{SFR} \sim M_{DG} \]

\[ \text{SFR} = \epsilon_{SF} \frac{M_{DG}}{\tau_{SF}} \]

*If: SFR \sim M_{DG} \ Then: \ \tau_{SF} = \text{const.}*

[Graph showing the relationship between IR luminosity and HCN line luminosity, with a linear fit equation: \( Y = 1.01X + 2.83 \).]
What determines the Star Formation Rate?

\[ \text{SFR} \sim M_{DG} \]

If: \( \text{SFR} \sim M_{DG} \)  Then: \( \tau_{SF} = \text{const.} \)

And this implies a *density threshold* for star formation:

\[ \text{SFR} = \epsilon_{SF} \frac{M_{DG}}{\tau_{SF}} \]

Wu et al. 2005
What determines the Star Formation Rate?

\[ \text{SFR} \sim \dot{M}_{DG} \]

\[ \text{SFR} = \varepsilon_{SF} \frac{\dot{M}_{DG}}{\tau_{SF}} \]

If: \( \text{SFR} \sim \dot{M}_{DG} \)  
Then: \( \tau_{SF} = \text{const.} \)

And this implies a density threshold for star formation:

\[ \tau_{SF} \sim \tau_{ff} \sim (G\rho_t)^{-1/2} \]
The End
KPNO Summer 1970