ORIGIN OF THE SOLAR SYSTEM

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An appendix with more complete notes including derivations of the Jeans Criteria and more detailed development of the angular momentum barrier are given.

The following are copies of the overheads shown in class.

On pp. 6 + 9 you should check the appendix for derivations and a more complete discussion.

Where are stars formed?

In molecular clouds

cold, neutral, molecular gas + dust clouds.

Evidence: All $*$s in process of forming are found in mol. clouds

All very young $*$ clusters are found in or near mol. clouds.

What do mol. clouds look like?

Opaque at UV + visible wavelengths

Bright + luminous at IR wavelengths

Bright rotational + vibrational molecular emission lines at radio + IR wavelengths

OH - mol. species #1

3 slides

Properties of Mol. Clouds

Cold: $8 \le T_{kin} \le 20K$ Typical $\sim 10K$

Low ionization: $n_e/n \simeq 10^{-6} - 10^{-7} \Rightarrow$ very neutral

high density: $n(H_2) \ge 10^3 \text{ cm}^{-3}$

Massive: $M \sim 10^4 - 10^6 M_\odot$

Large: $D \sim 300$ ly

Clumpy

Supersonic gas motions: $\Delta v \sim 0.5 - 2 \text{ km s}^{-1}$

$v_s \sim 0.2 \text{ km s}^{-1}$

Interstellar Molecules

Species	Name
H_2	molecular hydrogen
C_2	diatomic carbon
CH	methylidyne
CH^+	methylidyne ion
CN	cyanogen
CO	carbon monoxide
CS	carbon monosulfide
OH	hydroxyl
HCl	hydrogen chloride
NO	nitirc oxide
NS	nitrogen sulfide
SiC	silicon carbide*
SiO	silicon monoxide
SiS	silicon sulfide
SO	sulfur monoxide
PN	
CP	*
SO^+	sulfoxide ion
NaCl	sodium chloride*
AlCl	aluminum chloride*
KCl	potassium chloride*
AlF	aluminum fluoride*†
H_2D^+	†
C_2H	ethynyl
CH_2	methylene †
● HCN	hydrogen cyanide
HNC	hydrogen isocyanide
HCO	formyl
HCO^+	formyl ion
HOC^+	isoformyl ion †
N_2H^+	protonated nitrogen
HNO	nitroxyl
● H_2O	water
OCS	carbonyl sulfide
SO_2	sulfur dioxide
SiC_2	cilicon dicarbide (silacyclopropyne)*
C_2S	
C_2O	dicarbon monoxide †
C_3	triatomic carbon*
C_2H_2	acetylene
C_3H	propynylidyne (l and c)
● H_2CO	formaldehyde
$HCOOCH_3$	methyl formate
CH_3C_3N	methylcyanoacetylene
CH_3C_4H	methyldiacetylene
CH_3CH_3O	dimethyl ether
CH_3CH_2CN	ethyl cyanide
CH_3CH_2OH	ethanol

Species	Name
● NH_3	ammonia
HNCO	isocyanic acid
$NOCO^+$	protonated carbon dioxide
$HCNH^+$	protonated hydrogen dioxide
HNCS	isothiocyanic acid
C_3N	cyanoethynyl
C_3O	tricarbon monoxide
H_2CS	thioformaldehyde
H_3O^+	hydronium ion
C_3S	
C_4H	butadiynyl
C_3H_2	cyclopropenylidene
H_2CCC	propadienylidene
HCOOH	formic acid
CH_2CO	ketene
HC_3N	cyanoacetylene
CH_2CN	cyanomethyl
NH_2CN	cyanamide
CH_2NH	methanimine
● CH_4	methane
SiH_4	silane*
C_4Si	*
C_5	pentatomic carbon*
C_5H	pentynylidyne
C_2H_4	ethylene*
H_2CCCC	butatrienylidene
CH_3OH	methanol
CH_3CN	methyl cyanide
CH_3NC	methyl isocyanide
CH_3SH	methyl mercaptan
NH_2CHO	formamide
HC_3HO	propynal
C_5O	pentacarbon monoxide †
C_6H	
CH_2CHCN	vinyl cyanide
CH_3C_2H	methylacetylene
● CH_3CHO	acetaldehyde
CH_3NH_2	methylamine
HC_5N	cyanodiacetylene
HC_7N	cyanohexatriyne
CH_3C_4CN	
CH_3CH_3CO	acetone †
HC_9N	cyano-octa-tetra-yne
$HC_{11}N$	cyano-deca-penta-yne

* Detected in circumstellar envelopes only
† tentative

OH #1

Conditions that favor initiation of star formation:

Decrease internal pressure

by decreasing T or ρ or both

or by increasing the mean mass per particle

by transforming from an atomic → mol. gas.

or by decreasing the ionization fraction $f_e = n_e/n$ to $< 10^{-7}$ ⇒ ~~gas~~ decouples from any magnetic field present

⇒ magnetic pressure can't support the cloud.

Increase the external pressure

By partially focused shocks

[4 slides M17]

by ionization of the gas around a molecular clump

[3 slides M16
2 slides M20]

Low Temp. low T_e
High Density large mass
Clumpy structure

favor * form

Mol. Clouds have the "right stuff" for * formation. Mols. are efficient coolants $\Rightarrow$ hard for mol. clouds to be heated to temps much above ~20K.

Systematics of the Solar System

1. Coplanar orbits of the planets
2. Planets have prograde revolution
3. All but Venus + Uranus have prograde rotation
4. Sun contains all the mass
5. Planets contain ~all the angular momentum (mostly ♃ + ♄)
6. Small, dense, silicate + iron rich planets in the inner 2 AU (slow rotors, few or no moons, no rings) $\rho \sim 3\text{-}5$ gm cm^{-3}
7. Large, low density, gaseous planets in the outer solar system ($\gtrsim 5$ AU). (composition ~ sun, low ρ, many moons, ring systems)
8. Abundance gradient
   Low abund. of volatiles (H, He, Li ..) in inner solar system.
   Outer solar system abunds. like that of sun.
9. Revolution of rings + moons are all prograde for natural moons (those not believed to be captured).

Any successful theory for the origin of the solar system must account for these systematics.

There are two fundamental problems with understanding how stars and Planets form.

1. How does a cloud become gravitationally unstable in the first place? What initiates it?

2. How do stars shed angular momentum to allow matter to fall onto a forming protostar?

Jeans Criteria

For gravitationally bound cloud we require that gravitational potential energy be greater than the internal thermal energy.

For a cloud of density ρ, temperature T, and mean mass per particle μ:

The minimum radius for which the cloud is just balanced against gravity is:

$$R_J \approx (kT/G\mu\rho)^{1/2}$$

and the minimum mass for stability is

$$M_J \propto \left(\frac{T}{\mu}\right)^{3/2} \frac{1}{\sqrt{\rho}}$$

$n = \rho/\mu m_H$

For example: $n = 10^3\ \mathrm{cm}^{-3}$; $\mu = 2.25$ amu; $T = 10$ K

$R_J \sim 1.6 \times 10^{18}$ cm $\qquad M_J \sim 3.3\, M_\odot$

$\sim 104{,}000$ AU

$\sim 2.2 \times 10^7\, R_\odot$

Factors Favoring Star Formation

- Low Temp
- High Density
- High Mean mass/particle
- Low Ionization Fraction f_e
- Massive clouds
- Clumpy Structures

Molecular clouds provide these conditions

How might nature achieve the conditions to initiate star formation?

3 OHs #2, 3, 4

Increase in external pressure

Stellar induced * form.

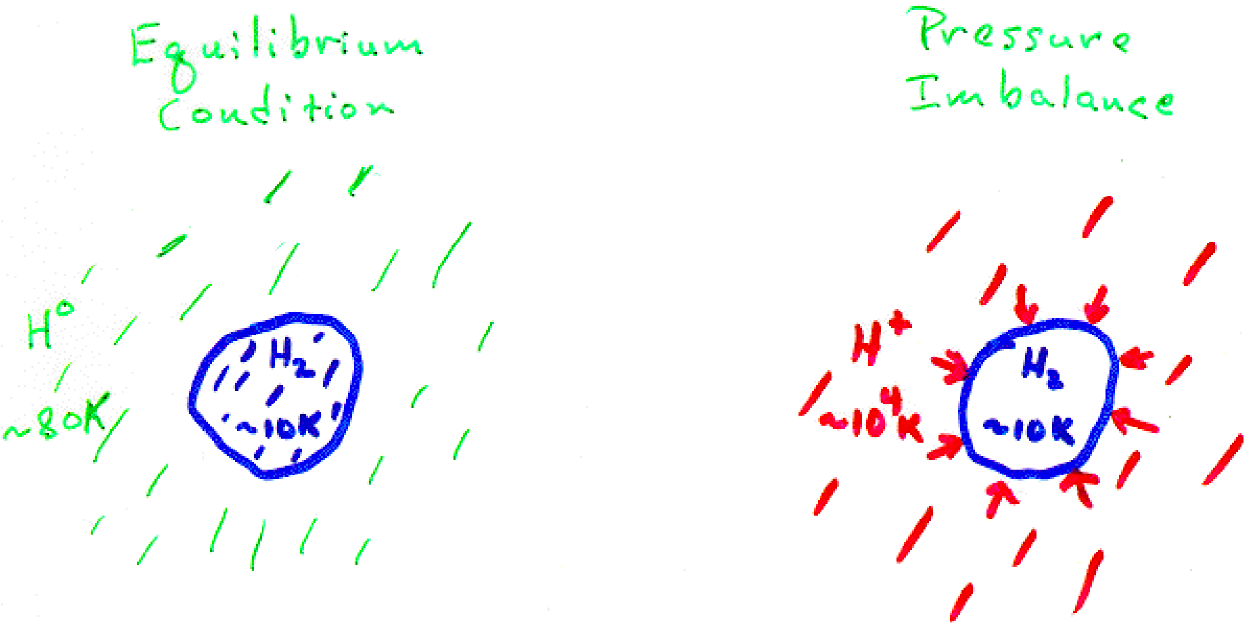
Shock induced * form.

5 Slides

3 - M16 showing erosion to reveal EGGs (evaporating gaseous globules)

2 - Rosette showing Bok Globules which probably contain EGGs.

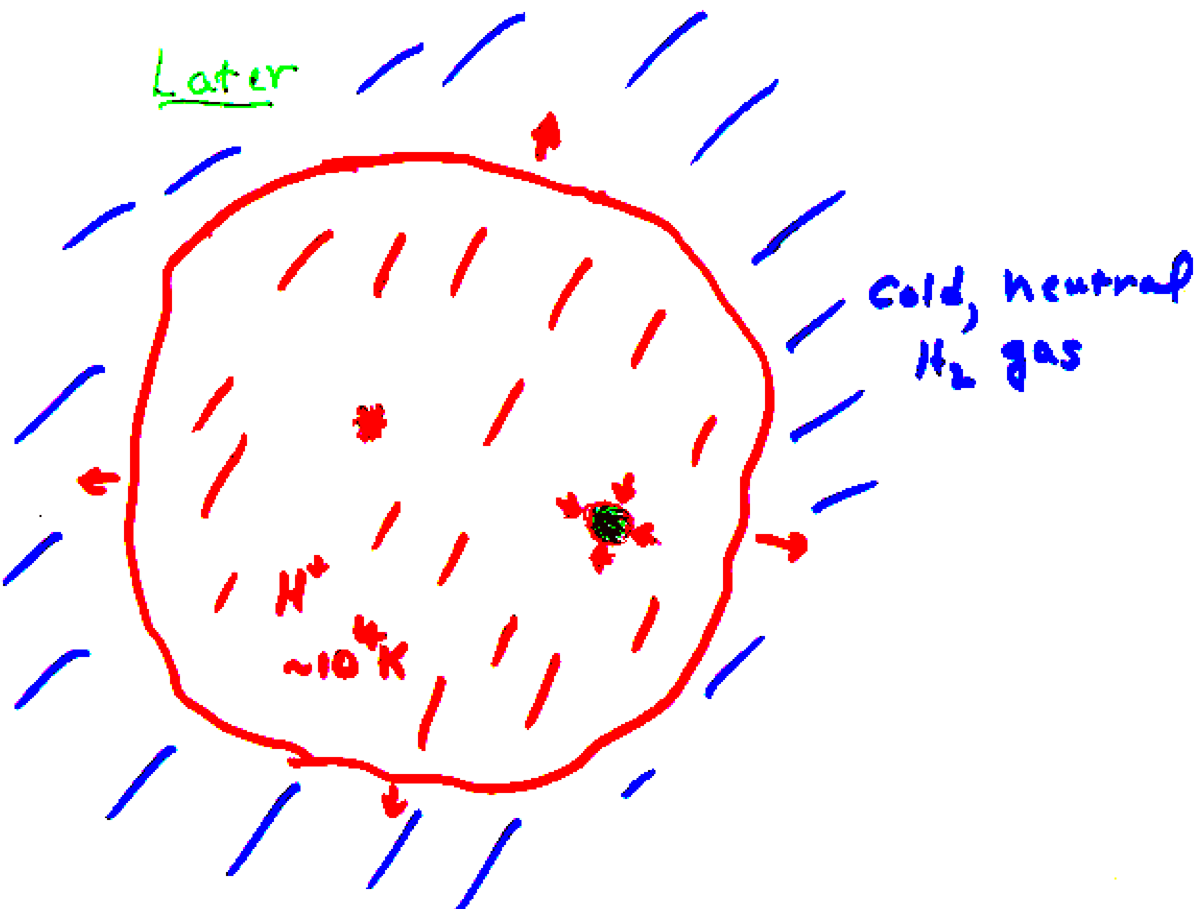
1 OH - Illustrating emergence of EGGs.
#5


Equilibrium Condition
H°
~80K
H₂
~10K
Pressure Imbalance
H⁺
~10⁴K
H₂
~10K

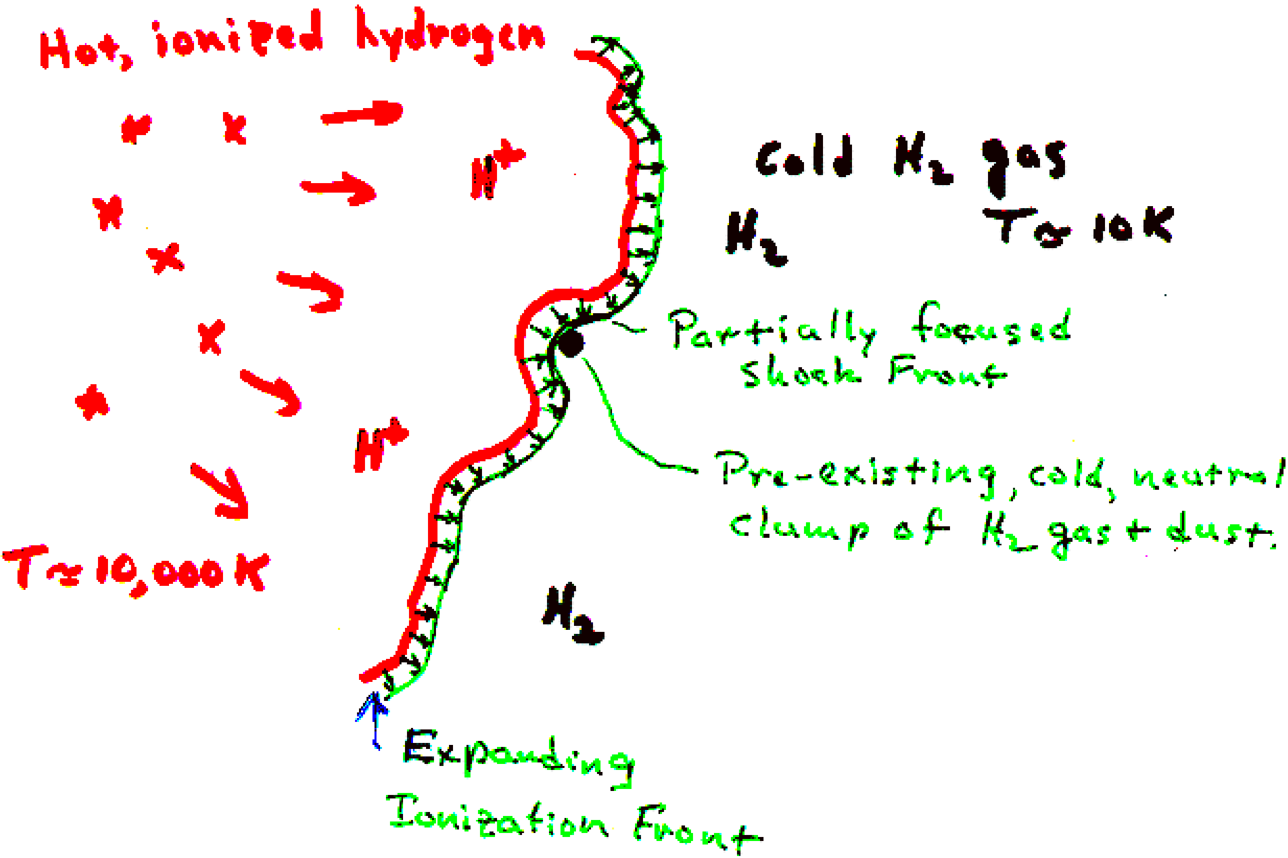
Stellar Induced Star Formation

Initial State

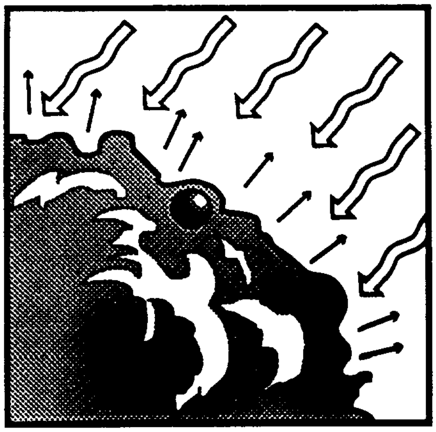
Later



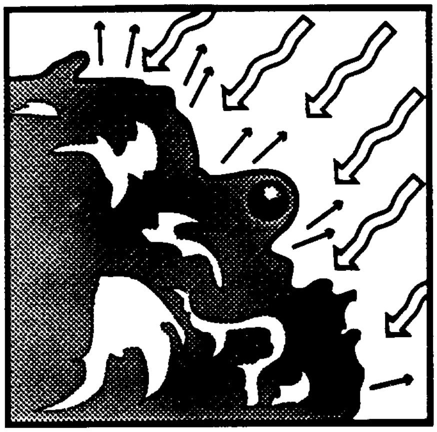
Schematic of Shock Induced Star Formation



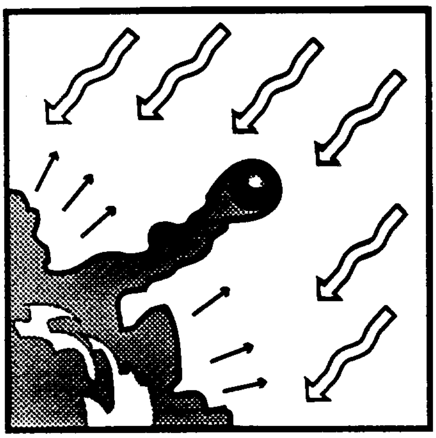
Stellar EGGs in M16



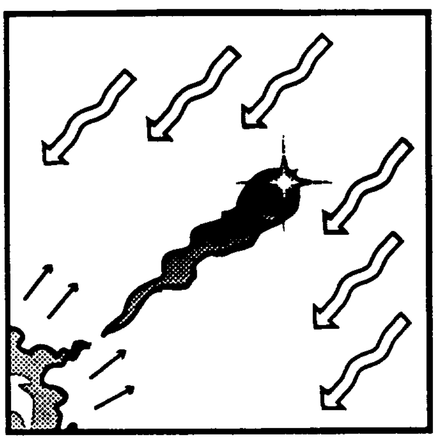
The surface of a molecular cloud is illuminated by intense ultraviolet radiation from nearby hot stars. The radiation evaporates material off of the surface of the cloud.



As the cloud is slowly eaten away by the ultraviolet radiation, a denser than average globule of gas begins to be uncovered



The EGG has now been largely uncovered. The shadow of the EGG protects a column of gas behind it, giving it a finger-like appearance.



Eventually the EGG may become totally separated from teh molecular cloud in which it formed. As the EGG itself slowly evaporates, the star within is uncovered and may appear sitting on the front surface of the EGG.

Why is it difficult to get matter onto the protostar?

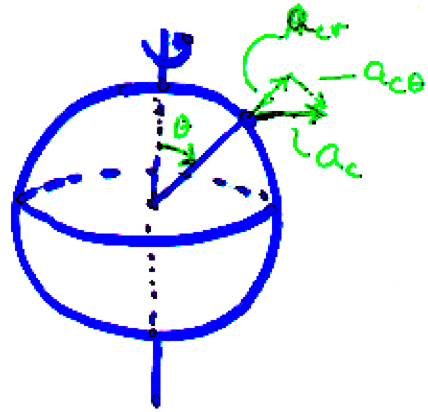
Cons. of Angular Momentum

⇒ spin-up as r decreases

$$a_g(r) \propto 1/r^2$$

Opposing this is a centrifugal term due to rotation

$$a_{cr}(\theta) \propto 1/r^3$$



⇒ a_{cr} increases faster than a_g as r decreases.

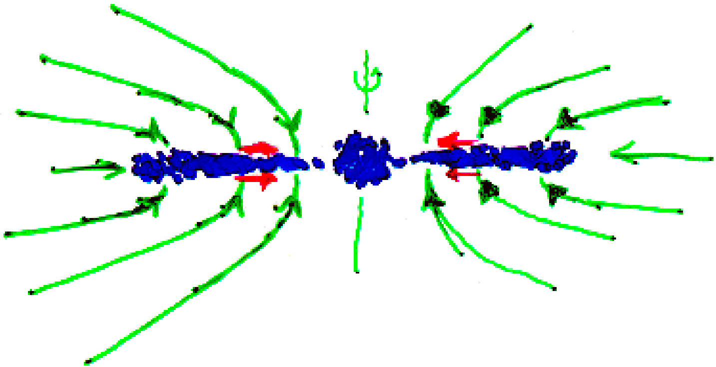
At small enough r: $a_{cr} \approx a_g$

+ no further collapse can occur!

Fragmentation to smaller clumps

Collapse of a fragment to a star via an accretion disk

Interplay between a_g + a_{cr} causes an accreting protostellar cloud core to form an <u>accretion disk</u>



Dilemma

Can't keep dropping high angular momentum mass onto a cloud core. It would soon reach critical speed, even with accretion through an accretion disk.

How does a protostar shed angular momentum?

Recall: $r_0 \rightarrow R_*$ is $\sim 10^7$ reduction.

$$\Rightarrow \omega_{R_*} \approx \omega_0 (r_0/R_*)^2$$ (ω is the angular speed)

$$\approx 10^{14} \omega_0$$

$$\Rightarrow P_* < 1^s \quad \text{but } P_\odot \sim 1 \text{ mo.}$$

A star sheds angular momentum by throwing mass out via bipolar outflows.

Stars shed angular momentum by forming bipolar jets

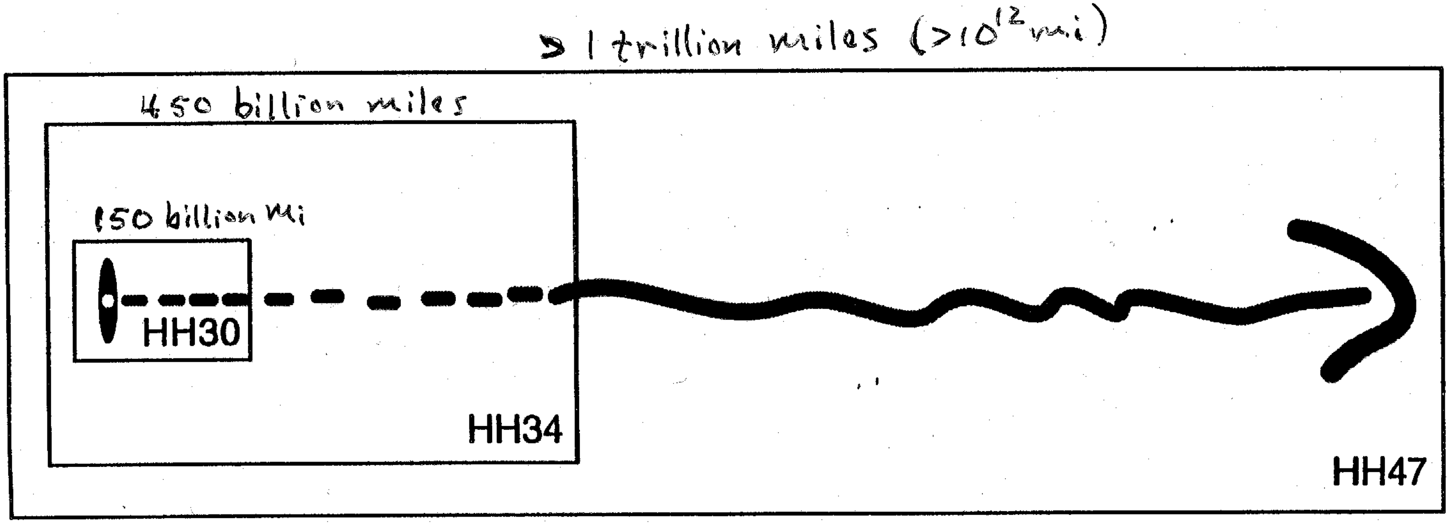


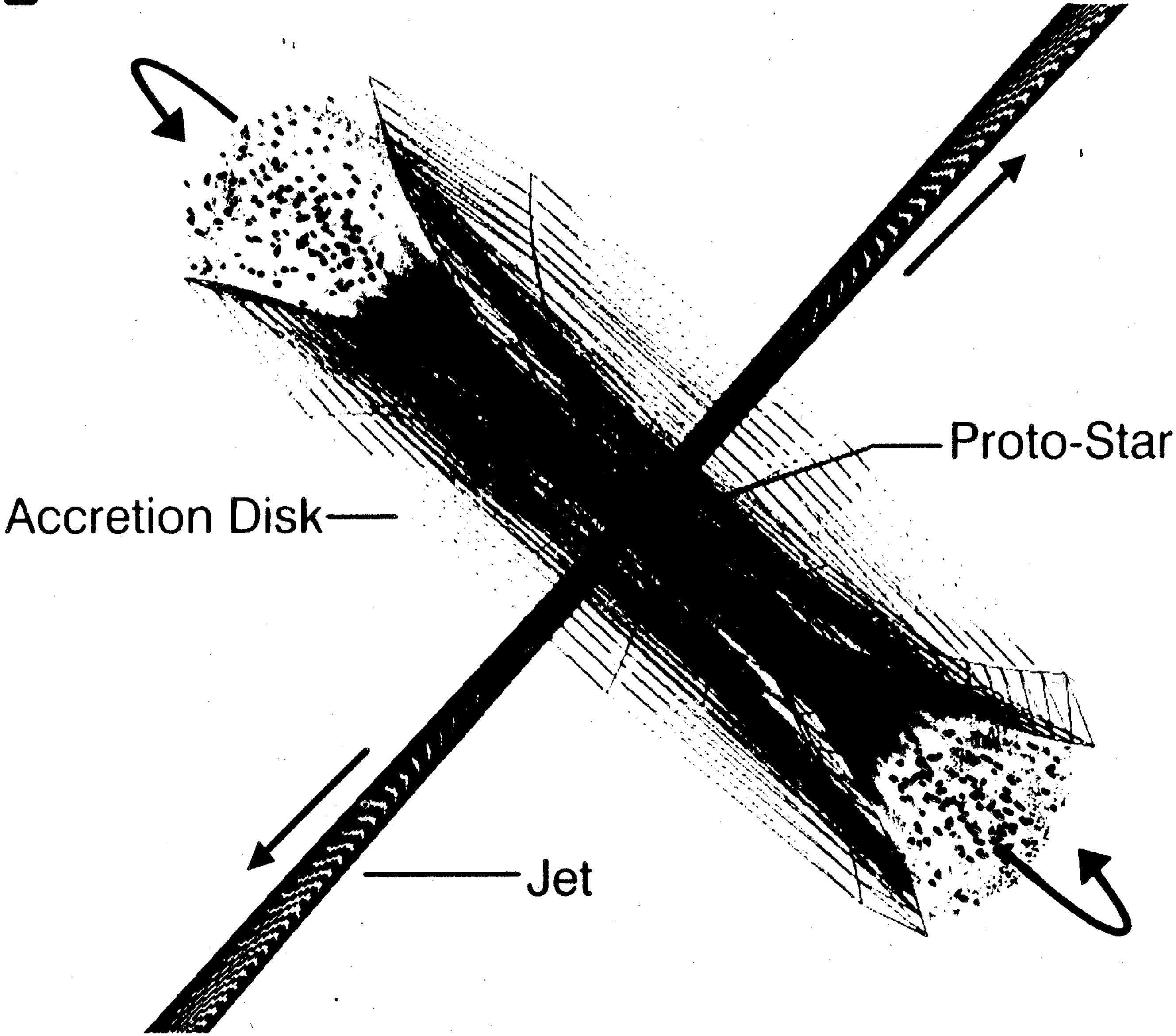
Diagram to accompany: *Jets From Young Stars* (prc-95-24a) Hubble Space Telescope Photo Release

This schematic shows the relative scale of Hubble Space Telescope images of stellar jets ejected from three different embryonic stars: HH30, HH34, and HH47. Though they are pictures of three different systems, when compared they provide a general view of how stellar jets behave as they propagate across space. The HH30 field of view, approximately 150 billion miles across, shows the jet as it emanates from a circumstellar disk that encircles a young star. The HH34 view, 450 billion miles across, shows that a jet remains narrow, and has a beaded structure. The HH47 view, more than a trillion miles across, shows how a jet plows through interstellar space, creating arrowhead-shaped bow shocks.

Destruction of Proto-Planetary Disks in Orion's Trapezium Explained

Schematic of a protostar with accretion disk + bipolar Jet.

Diagram of HH 30 Circumstellar Disk & Jet



Schematic of the Initial stages of star formation.

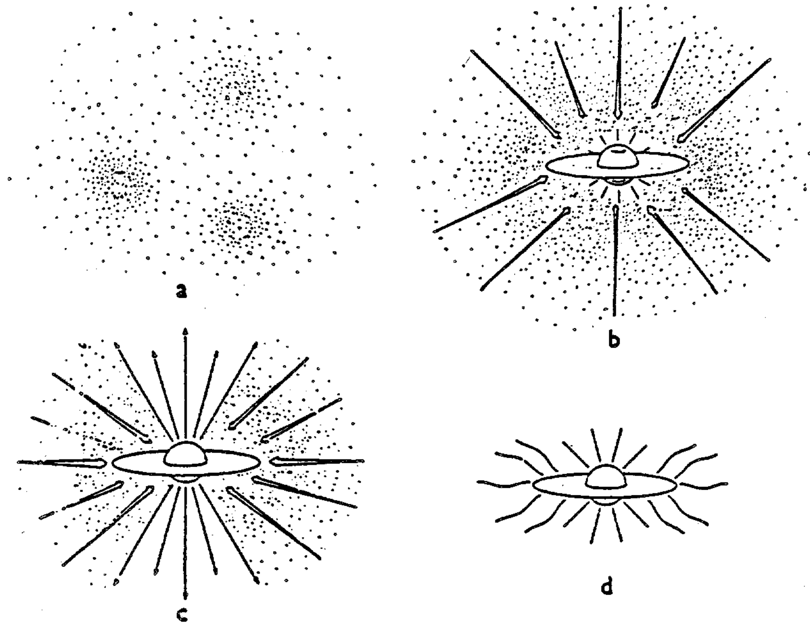


Figure 1. The four stages of star formation. (a) Cores form within molecular cloud envelopes as magnetic and turbulent support is lost through ambipolar diffusion. (b) Protostar with a surrounding nebular disk forms at the center of a cloud core collapsing from inside-out. (c) A stellar wind breaks out along the rotational axis of the system, creating a bipolar flow. (d) The infall terminates, revealing a newly formed star with a circumstellar disk. (From Shu, Adams, and Lizano 1987.)

Later Stage.

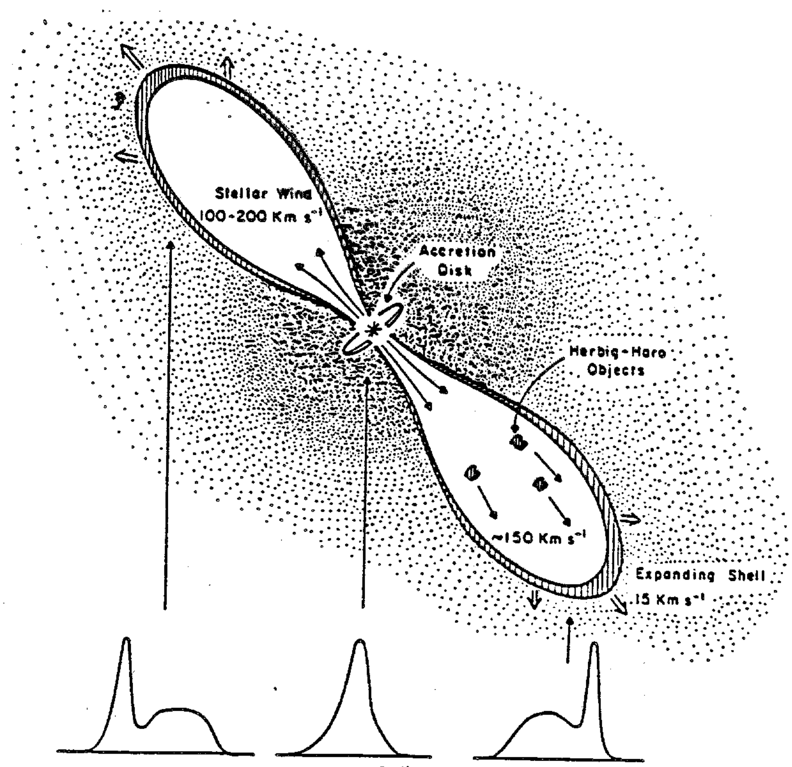


Figure 3. Schematic model for the bipolar flow in L1551 driven by a stellar wind emanating from IRS 5. At the bottom is depicted expected CO line profiles for different line of sights across the source. (From Snell, Loren, and Plambeck 1980.)

From accretion disk to planets

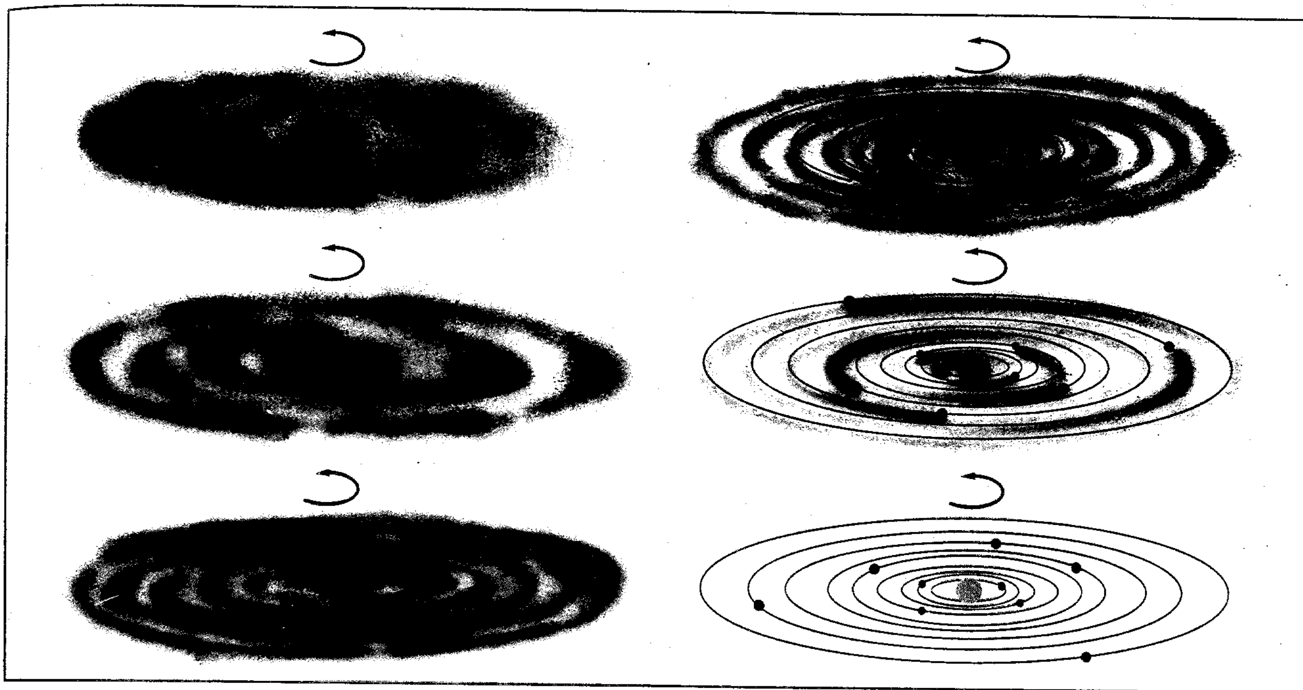


Figure 16.6 Steps in the Sun's formation. *An interstellar cloud, initially very extended and rotating very slowly, collapses under its own gravitation. This happens most quickly at the center. As the collapse occurs, the internal temperature rises and the rotation rate increases. Eventually the central condensation becomes hot and dense enough to be a star, with nuclear reactions in its core.*

Table 16.3 Timetable for solar system formation

Approximate Time	Event
0	Collapse of interstellar cloud; disk formation
400,000 years	Central condensation becomes hot enough for pressure to balance gravity; matter still falling in
1 million years	Second collapse stage is followed by new nearly stable phase, with heating by slow gravitational contraction; central object is now called the protosun; infalling gas and dust shrouds protosun from exterior view
1–10 million years	Planetesimals form and accrete to form planets
1–100 million years	T Tauri wind
100 million years	Start of nuclear reactions in core
0.1–1 billion years	Magnetic braking slows Sun's rotation; major cratering occurs throughout solar system

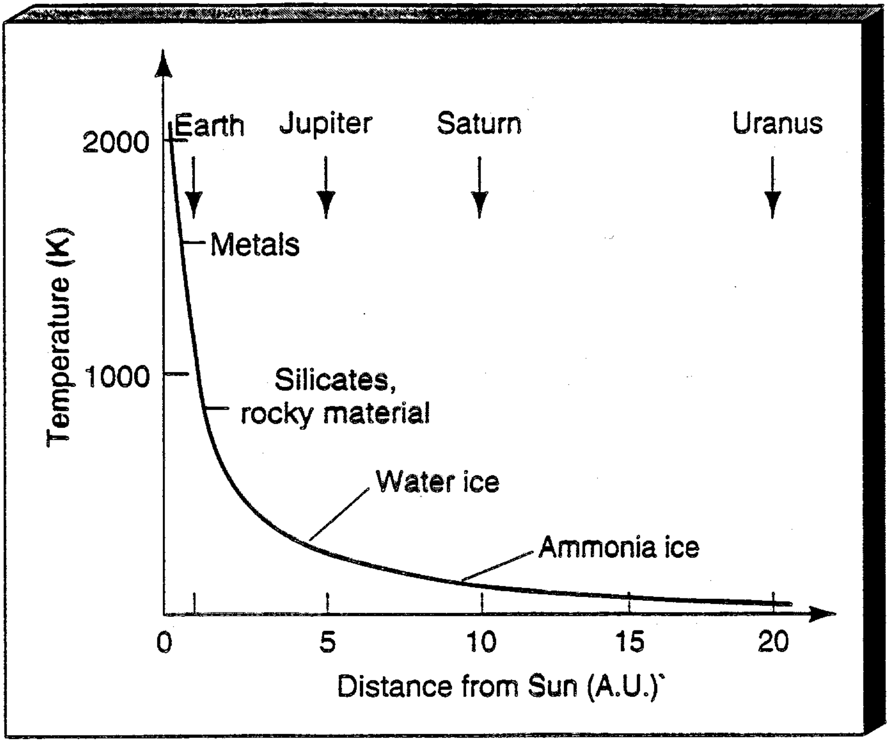


Figure 15.7 Theoretically computed variation of temperature across the primitive solar nebula. In the hot central regions, only metals could condense out of the gaseous state to form grains. At greater distances from the central protosun, the temperature was lower, so rocky and icy grains could also form. The labels indicate the minimum radii at which grains of various types could condense out of the nebula.

Accretion disk - bipolar jets account for:

1. Small, rocky, metal rich inner planets
   less matter near sun
2. Absence of volatile elements (H, He) in
   the inner solar system.
3. Prograde rotation + revolution of planets
   + true moons.
4. Co-planar planetary orbits
5. Massive outer planets composed mostly
   of H + He (similar comp. as the Sun).
6. Most angular momentum in the
   outer planets + most mass in the
   Sun.

Additional Material Can Be Referenced at the Fall'96 NEEP602 Website