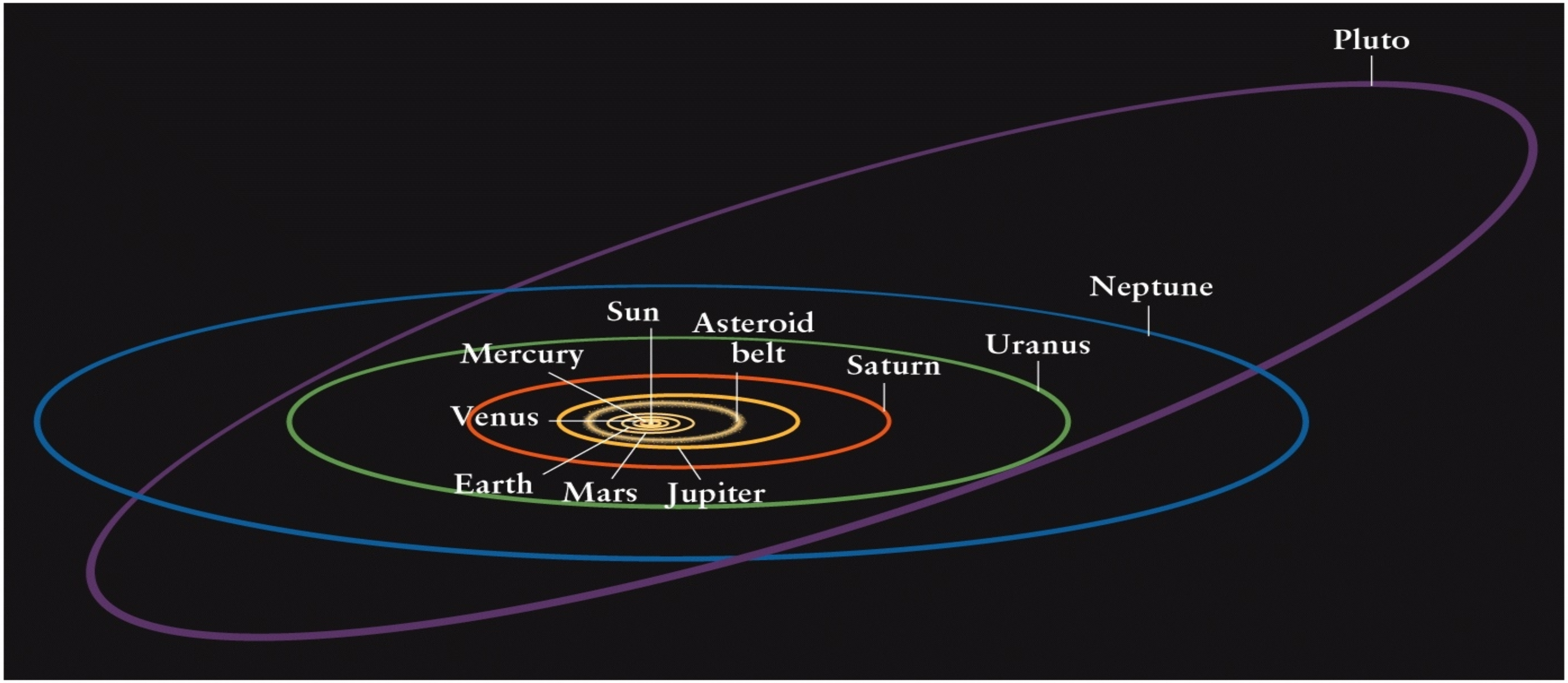
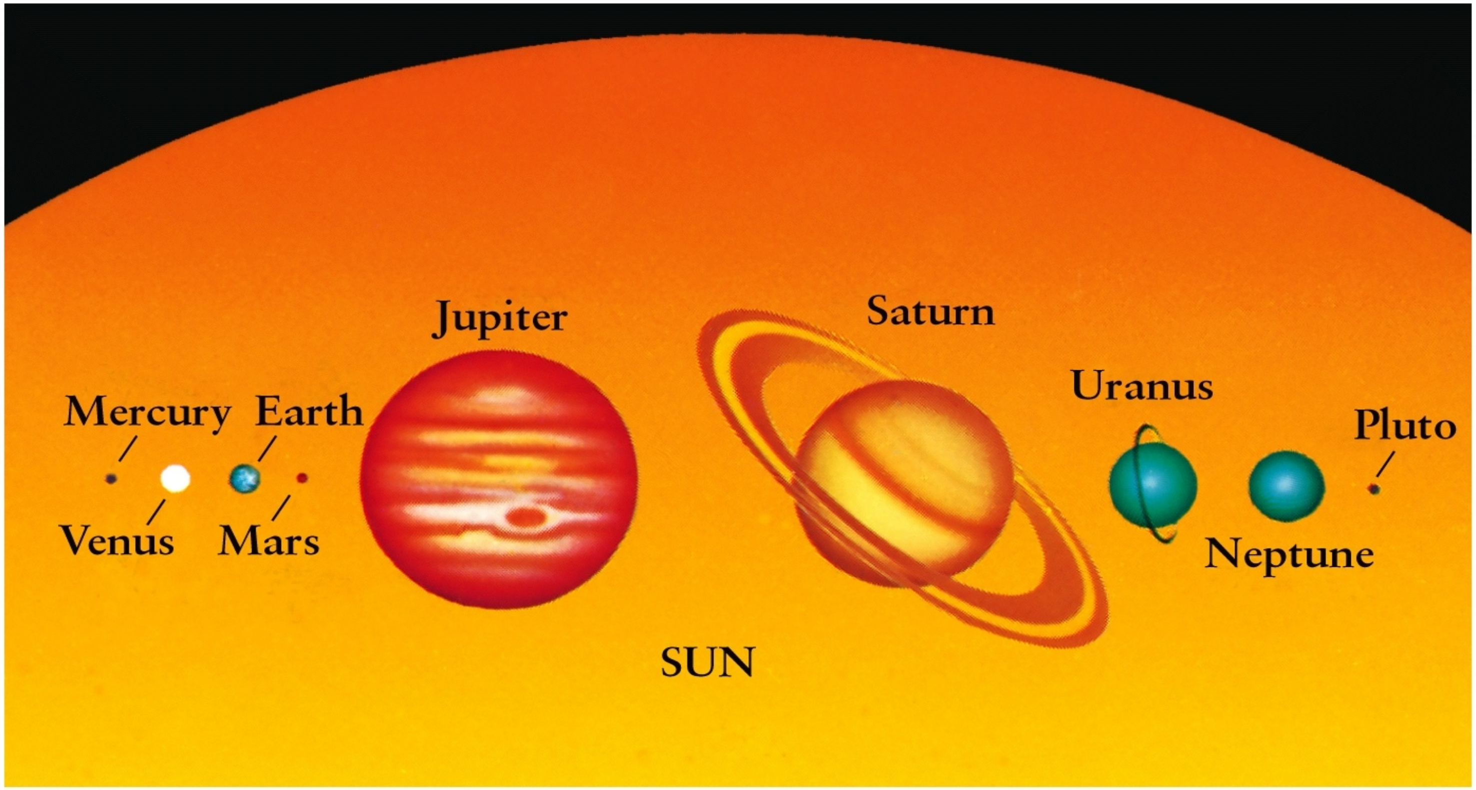
The formation of the Solar System
I. Stellar context

- What basic clues do we have about the formation of our Solar System?
- What is the astronomical context?
- What avenues do we have to learn more?





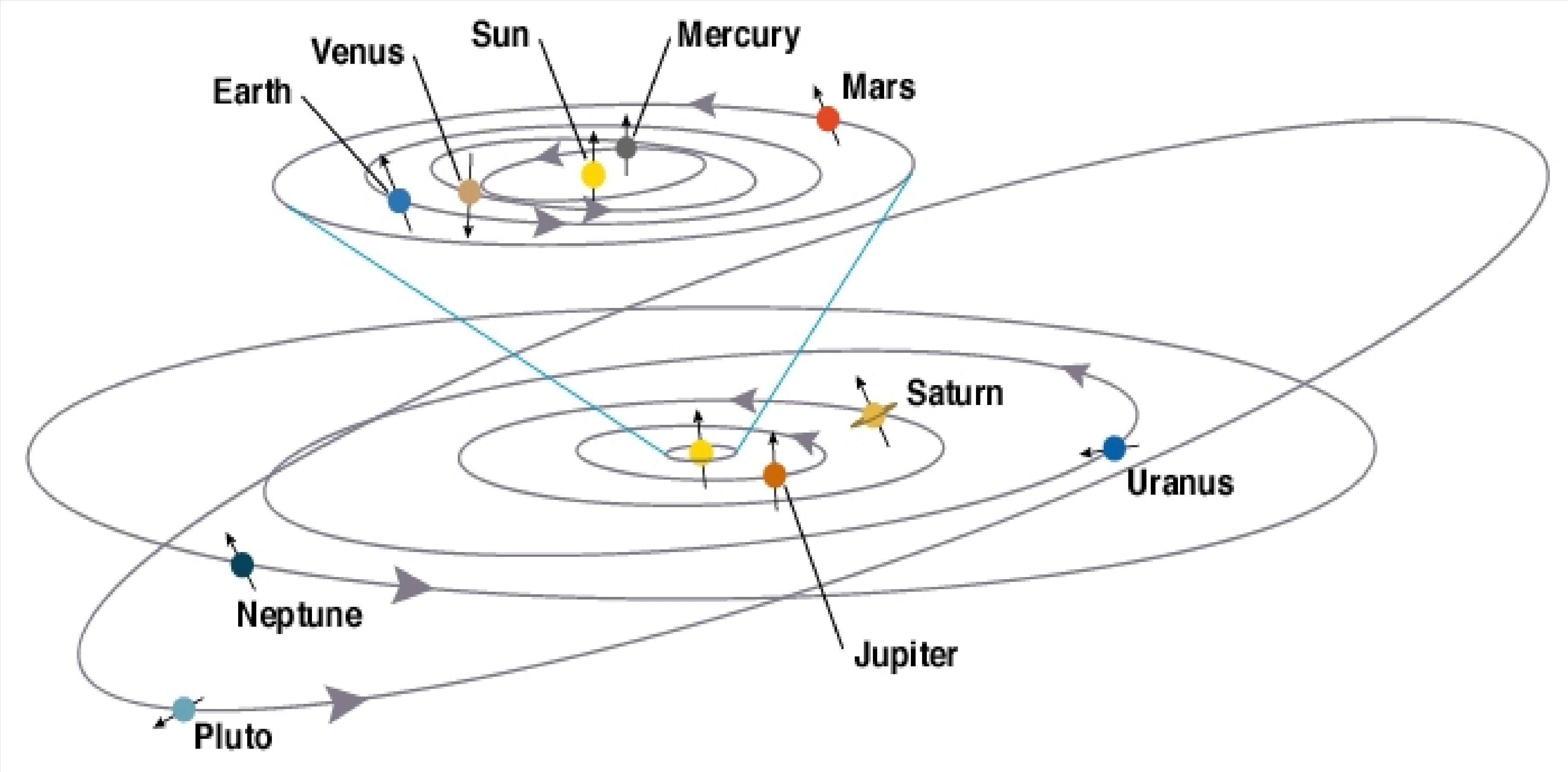
- What do we already know?

Basic patterns needing explanation

- All planets orbit Sun in same sense (counter-clockwise viewed from N)
- All planets orbit in almost same plane, with e~0
- Sun contains 99.9% of Solar System's mass.
- Inner planets rocky, outer planets/satellites icy or heavily gas-rich
- Very similar isotopic ratios of certain elements

The Layout of the Solar System

- Large bodies in the Solar System have orderly motions
  - planets orbit counterclockwise in same plane
  - orbits are almost circular
  - the Sun and most planets rotate counterclockwise
  - most moons orbit counterclockwise



Comparative Planetology

- Studying the similarities among and differences between the *planets*
  - this includes moons, asteroids, & comets
- This approach is useful for learning about:
  - the physical processes which shape the planets
  - the origin and history of our Solar System
  - the nature of planetary systems around other stars

The Layout of the Solar System

- Planets fall into two main categories
  - Terrestrial (i.e. Earth-like)
  - Jovian (i.e. Jupiter-like or gaseous)

Terrestrial Planets	Jovian Planets
Smaller size and mass	Larger size and mass
Higher density (rocks, metals)	Lower density (light gases, hydrogen compounds)
Solid surface	No solid surface
Closer to the Sun (and closer together)	Farther from the Sun (and farther apart)
Warmer	Cooler
Few (if any) moons and no rings	Rings and many moons

Photo	Planet	Average Distance from Sun (AU)	Temperature†	Relative Size	Average Equatorial Radius (km)	Average Density (g/cm^3)	Composition	Known Moons	Rings?
	Mercury	0.387	700 K		2,440	5.43	Rocks, metals	0	No
	Venus	0.723	740 K		6,051	5.24	Rocks, metals	0	No
	Earth	1.00	290 K		6,378	5.52	Rocks, metals	1	No
	Mars	1.52	240 K		3,397	3.93	Rocks, metals	2 (tiny)	No
	Most asteroids	2–3	170 K		≤500	1.5–3	Rocks, metals	?	No
	Jupiter	5.20	125 K		71,492	1.33	H, He, hydrogen compounds‡	28	Yes
	Saturn	9.53	95 K		60,268	0.70	H, He, hydrogen compounds‡	30	Yes
	Uranus	19.2	60 K		25,559	1.32	H, He, hydrogen compounds‡	21	Yes
	Neptune	30.1	60 K		24,764	1.64	H, He, hydrogen compounds‡	8	Yes
	Pluto	39.5	40 K		1,160	2.0	Ices, rock	1	No
	Most comets	10–50,000	A few K§		A few km?	<1?	Ices, dust	?	No

*Appendix C gives a more complete list of planetary properties.

Theories after the middle ages

Three types

- Collision (Buffon)
- Tidal (Jeans & Jeffries, Woolfson)
- Nebular (Kant, Laplace)

1+2 : Sun forms first, planets form later by accident

(Note: planetary sytems rare in this case)

3 : Sun and planets form simultaneously in spinning disk, naturally explaining planetary orbits.

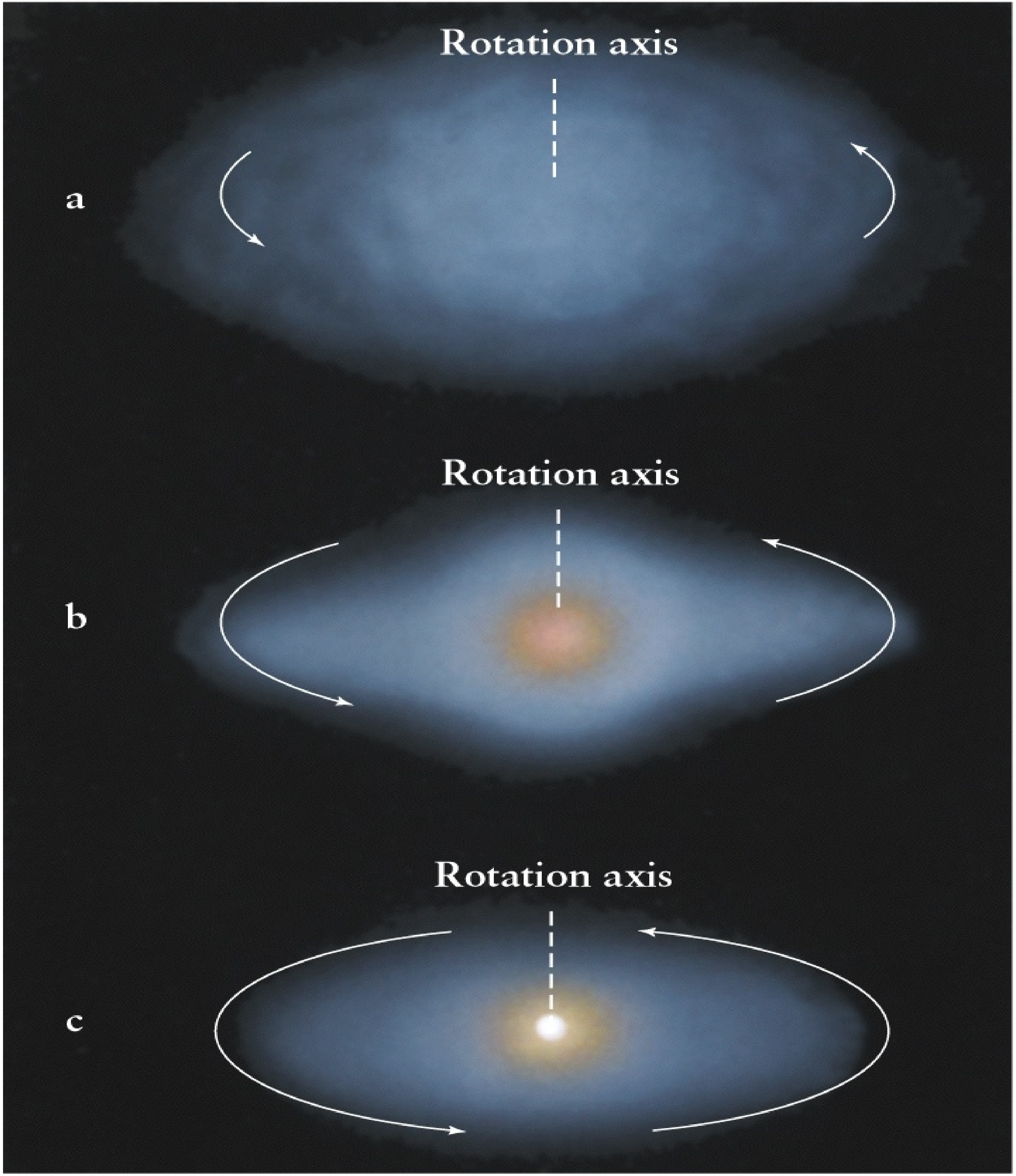
Cloud heats as it contracts.

Kelvin-Helmhotz heating

(conservation of energy)

Spins faster

Conservation of angular momentum

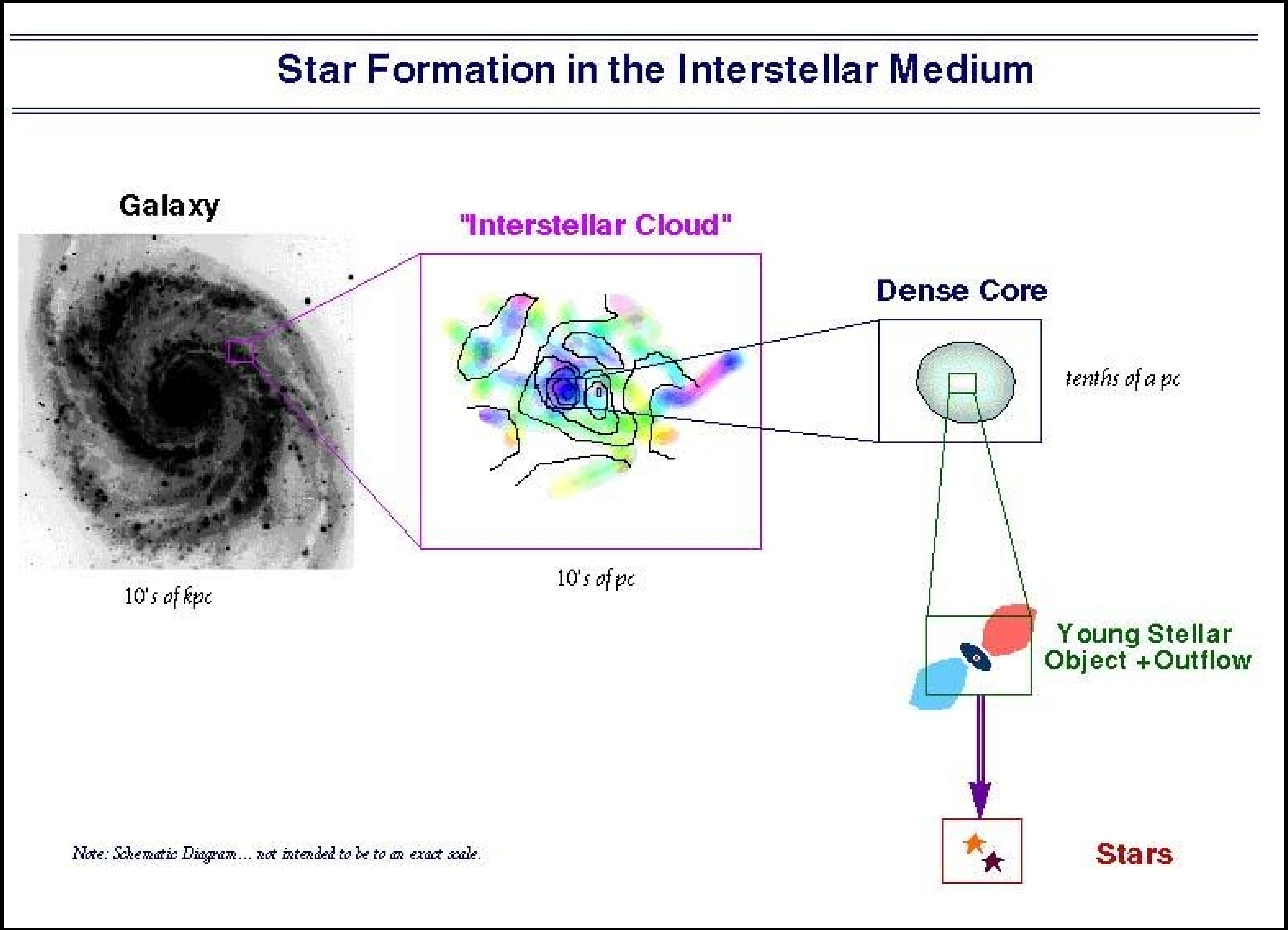


Nebular Theories

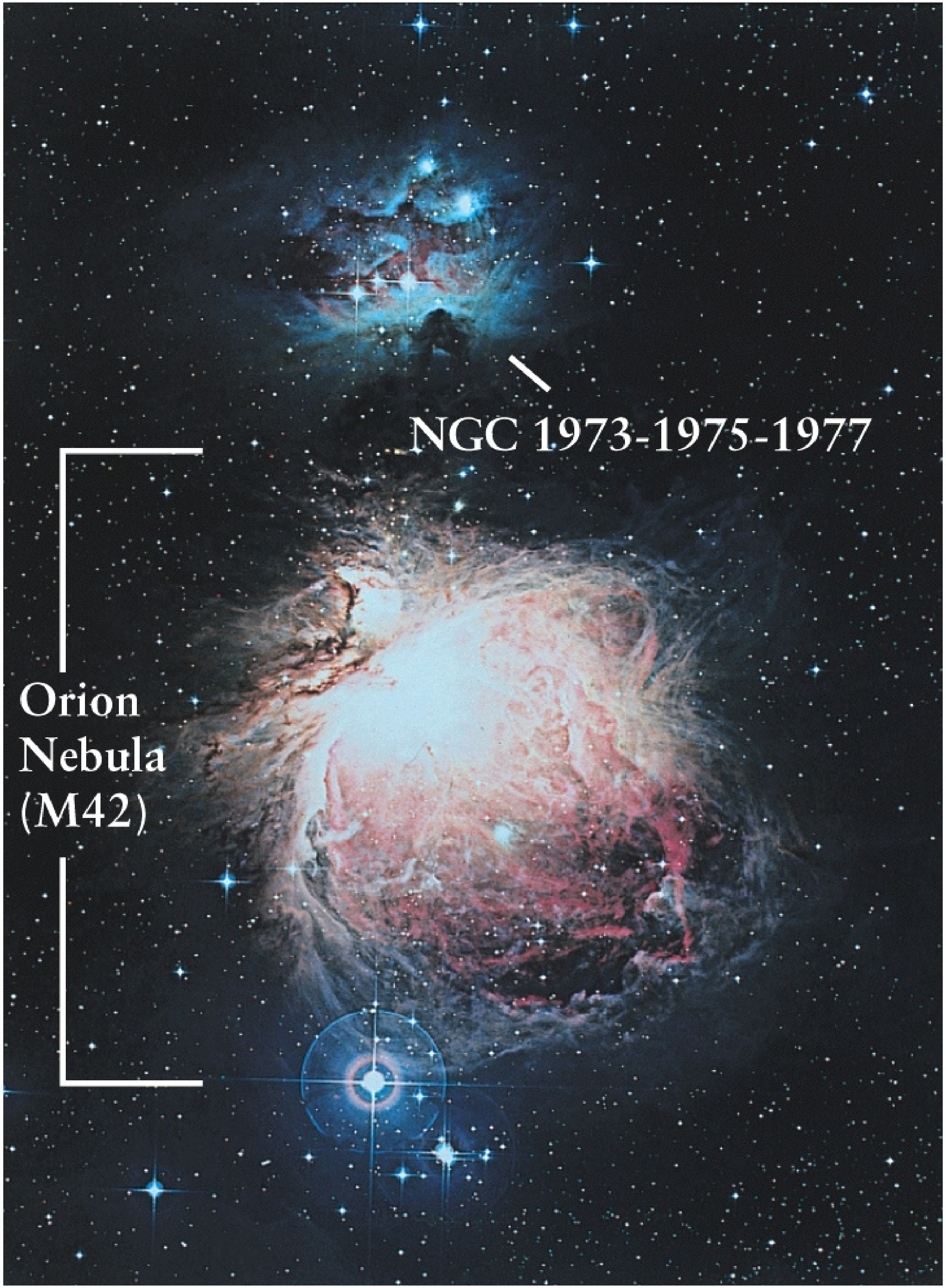
- Most popular
- Explain observed facts best

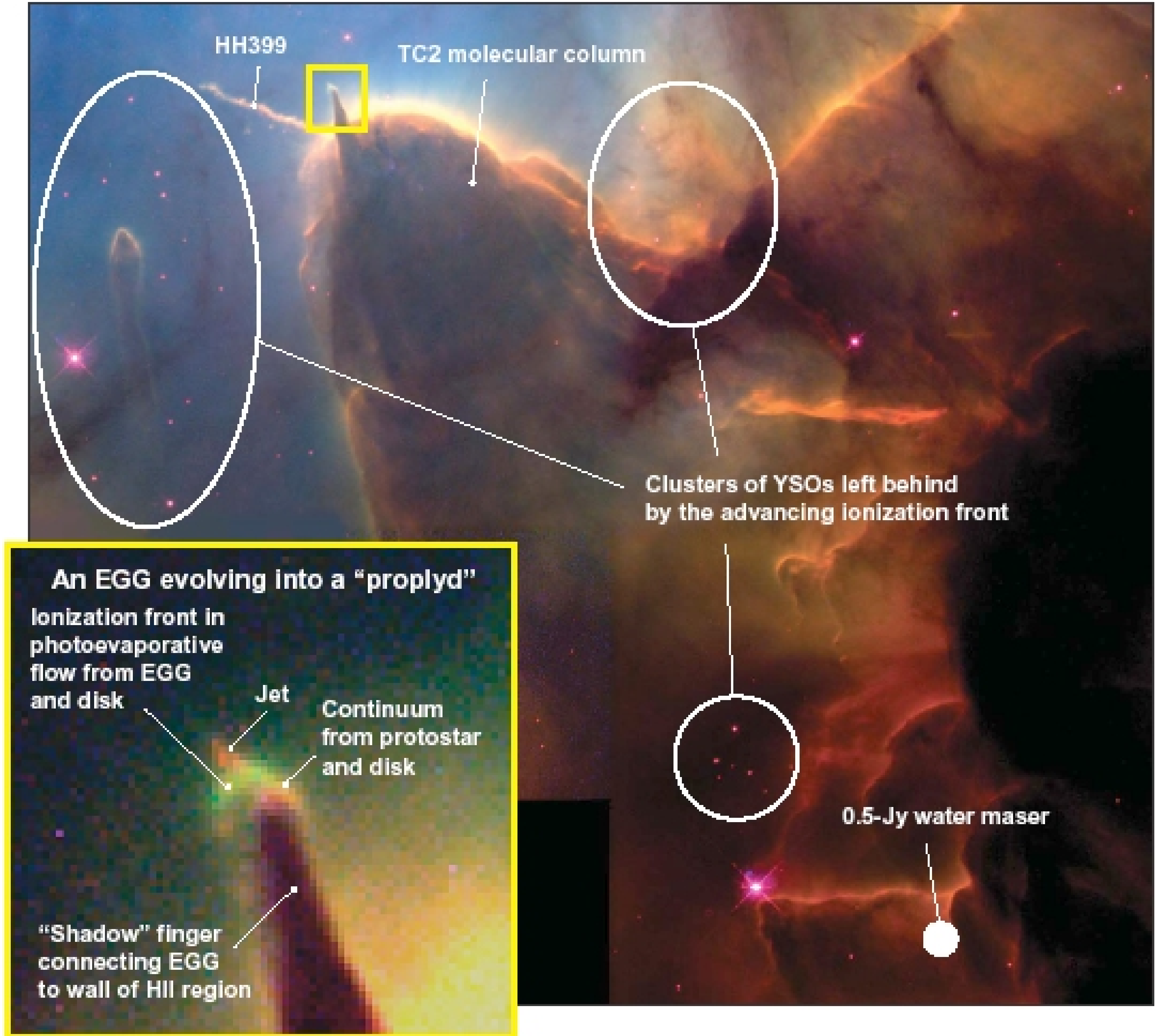
- Implies formation of Sun-like stars and planets is closely connected.
- There are billions of solar-type stars in the galaxy...are there billions of planets?
  - IS THERE ANY DIRECT EVIDENCE FOR THIS?

The framework - coupled to star formation

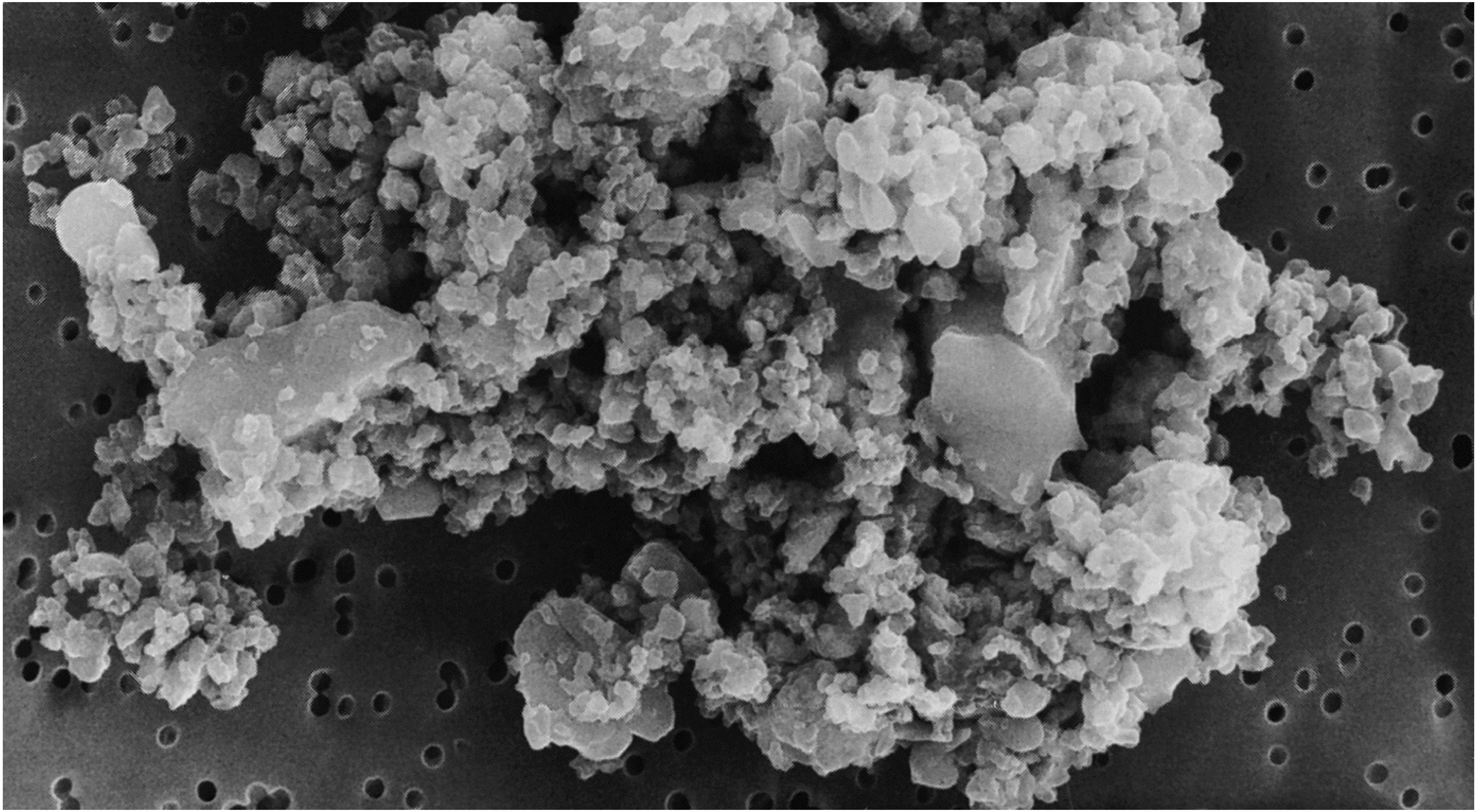


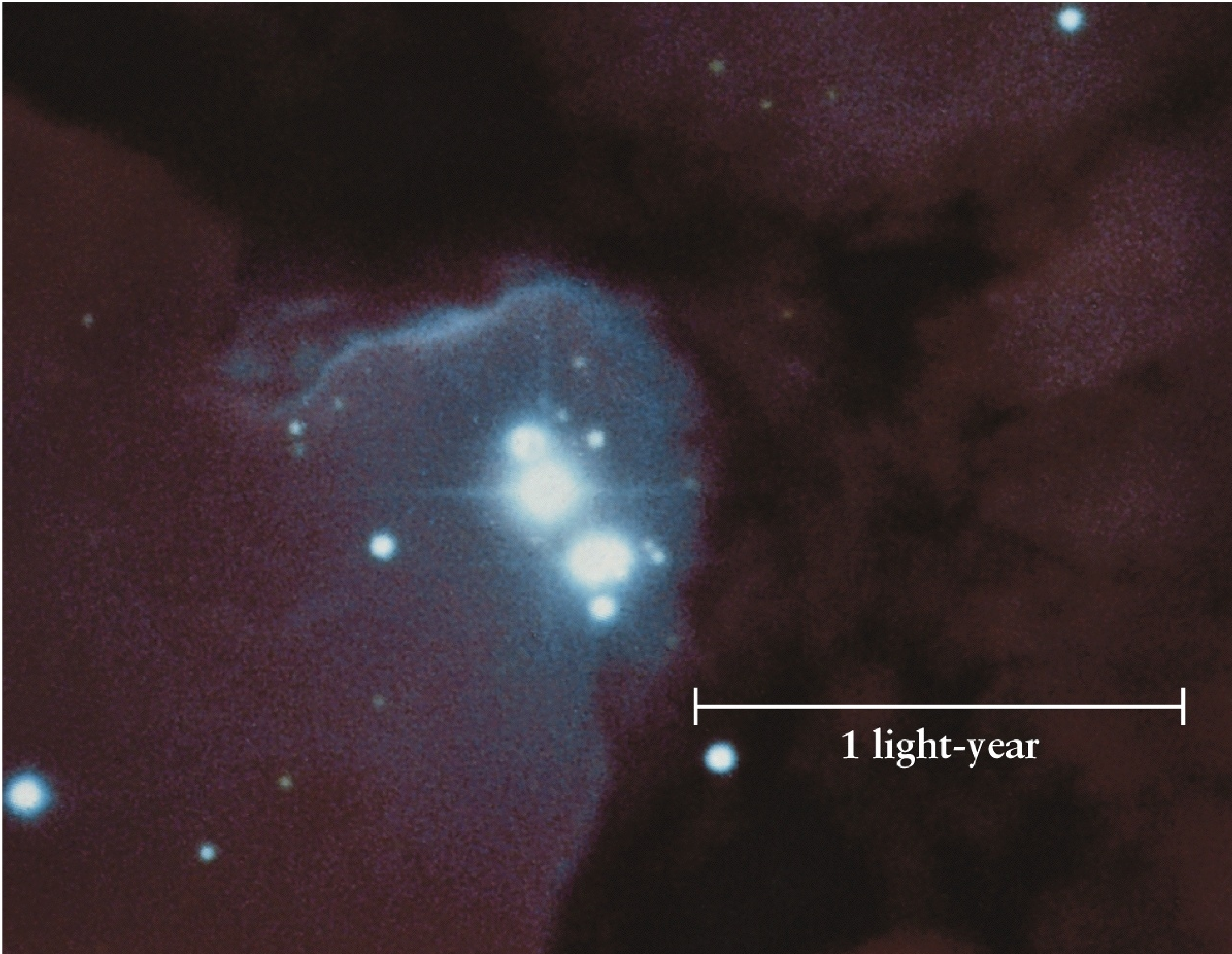
Young stars are found in our galaxy near regions of gas and dust.

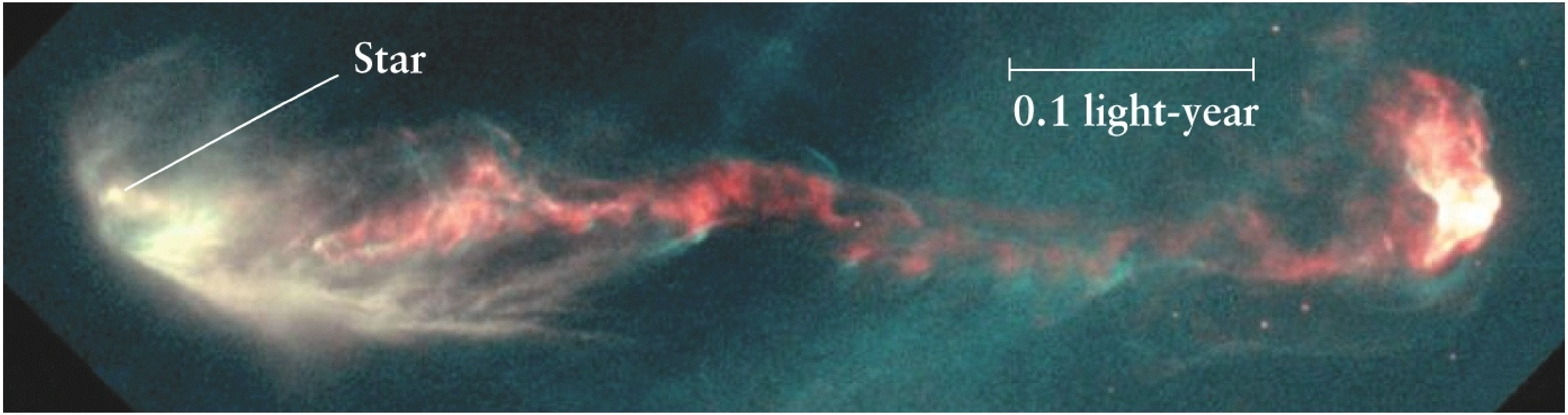



HH399
TC2 molecular column
Clusters of YSOs left behind
by the advancing ionization front
0.5-Jy water maser
An EGG evolving into a "proplyd"
Ionization front in
photoevaporative
flow from EGG
and disk
Jet
Continuum
from protostar
and disk
"Shadow" finger
connecting EGG
to wall of HII region

The 'dust' is in small complex grains (1-100 μm diameter)



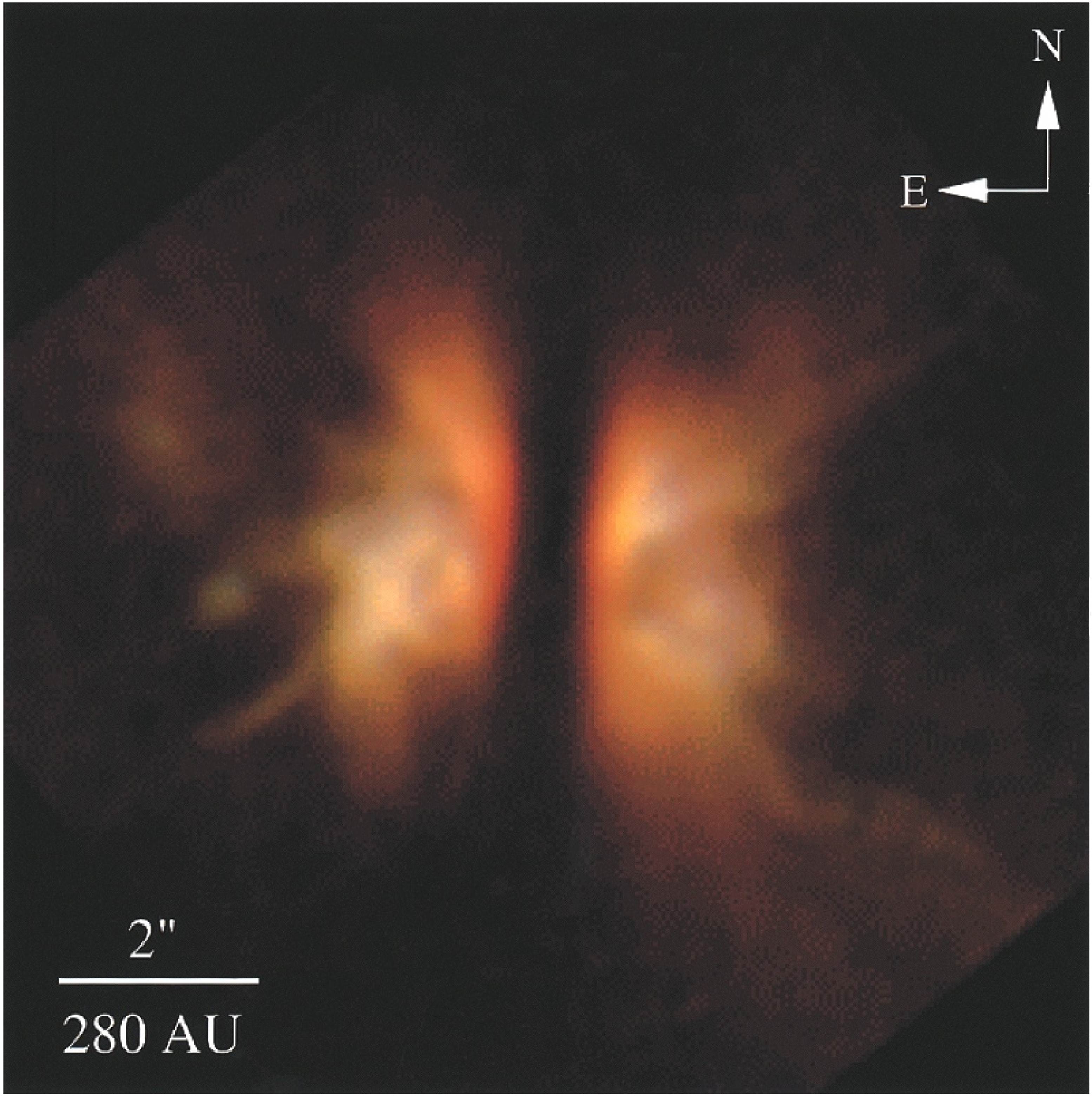

1 light-year

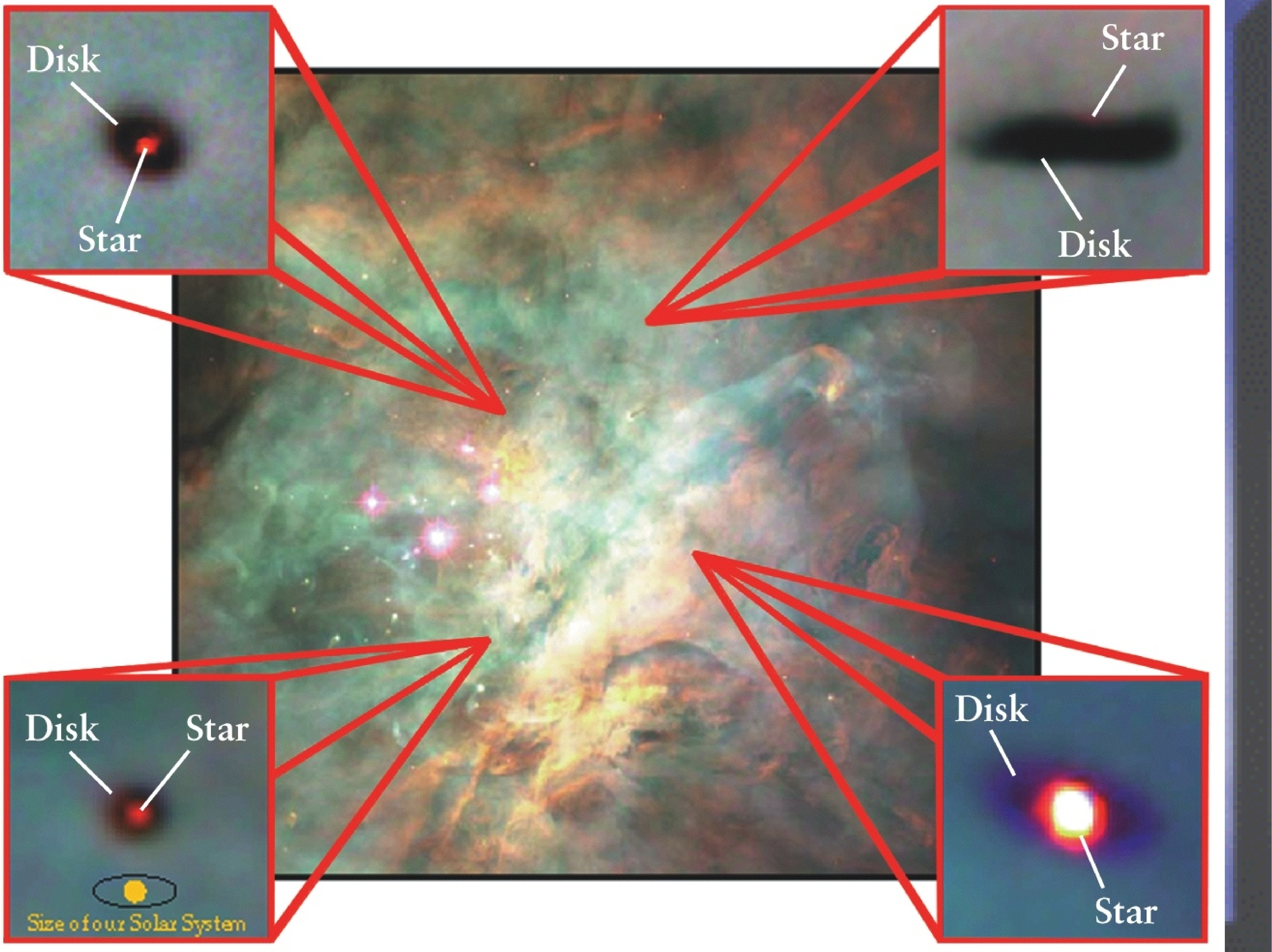


-The youngest stars are buried inside 'cocoons' of gas/dust.

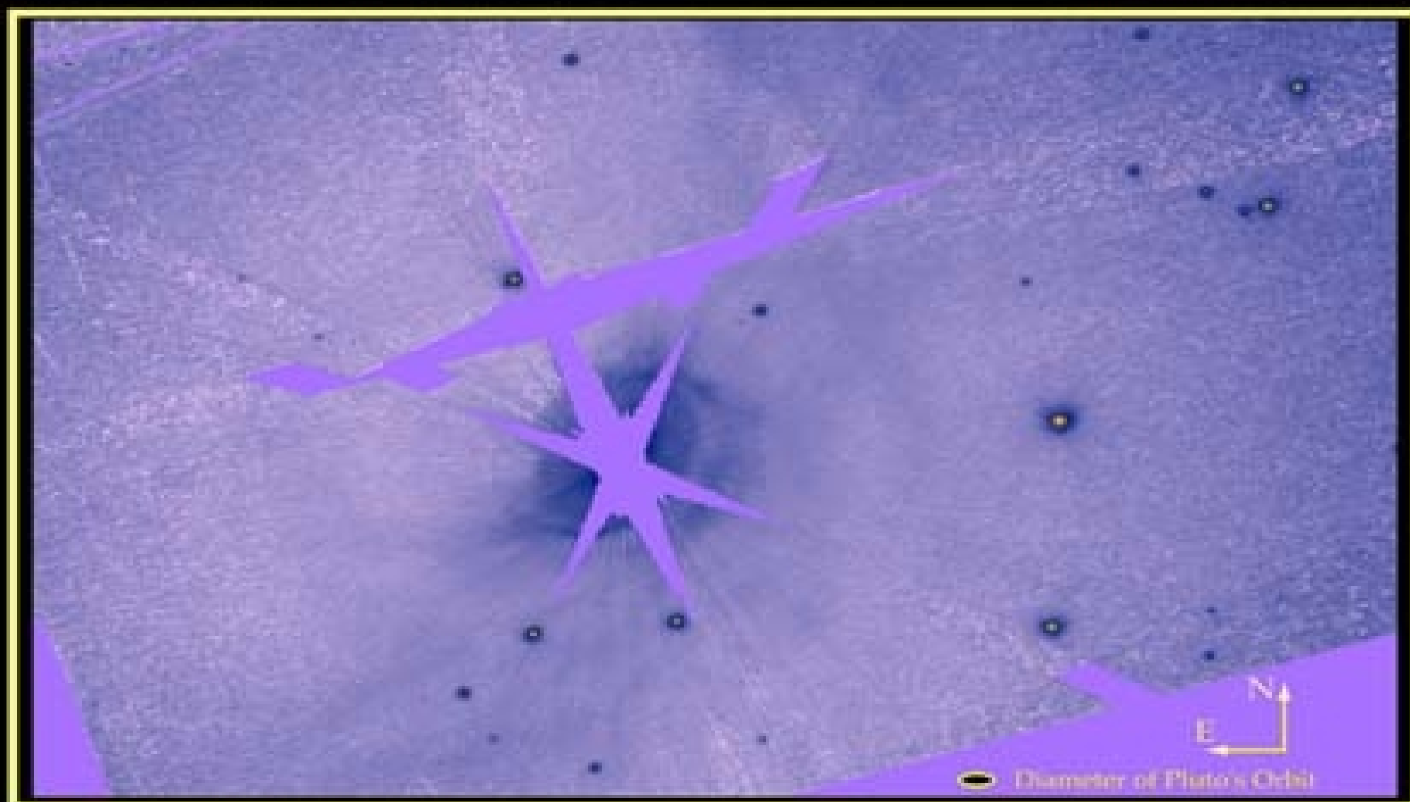
-They are often interacting violently with their surroundings

Some of these stars DO have disks around them!




Disk
Star
Star
Disk
Disk
Star
Size of our Solar System
Disk
Star

Disk are now directly imaged around other stars



The Disk and Environment of HD 100546

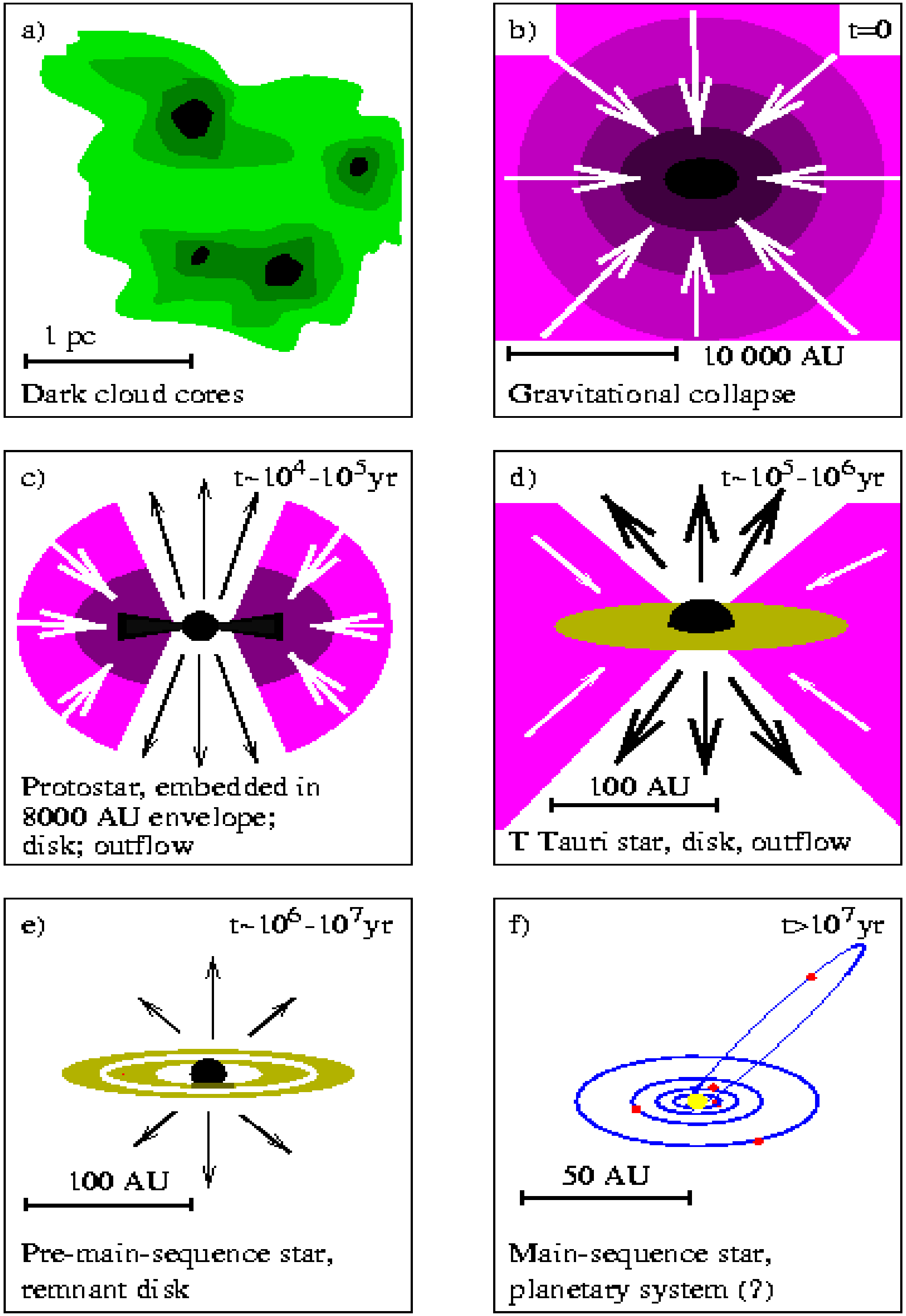
C.A. Grady (NOAO, GSFC) and the STIS Investigation Definition Team, NASA

Details of what is going on inside are still inaccesible to observations

4 stages in star/planet formation

1) 'Cores' form in molecular clouds, some collapse
2) Protostar and disk forms at center with while star is still cloaked inside infalling matter
3) Star eventually becomes powerful enough to create a 'wind' which breaks out along spin axis. Mass flows into star
4) Star blows away envelope, leaving disk in which planets form.

Timescales

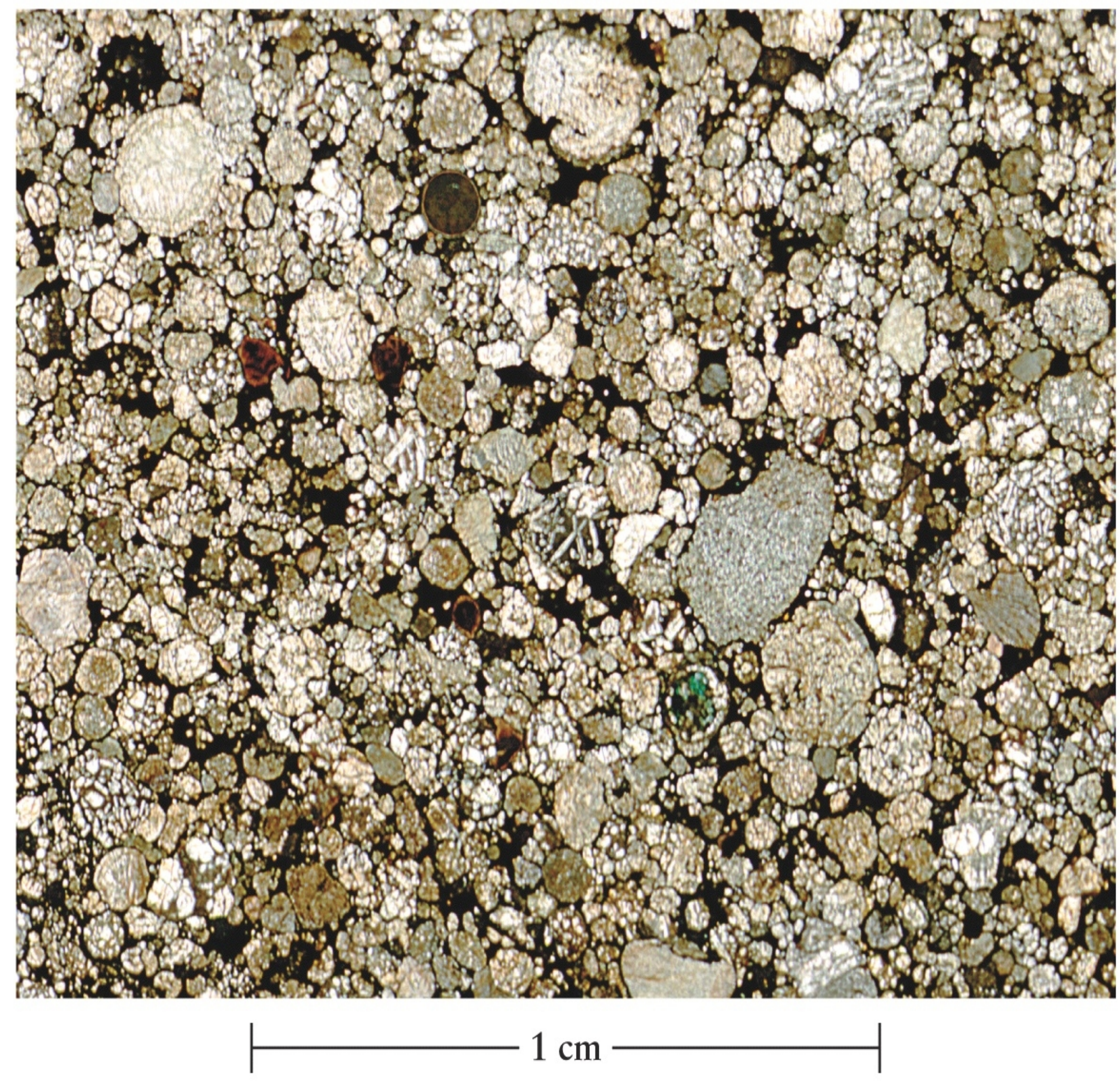


Hogerheijde 1998, after Shu et al. 1987

The protoplanetary accretion disk COMPOSITION

1) Consisted of same 'stuff' that makes up the Sun.

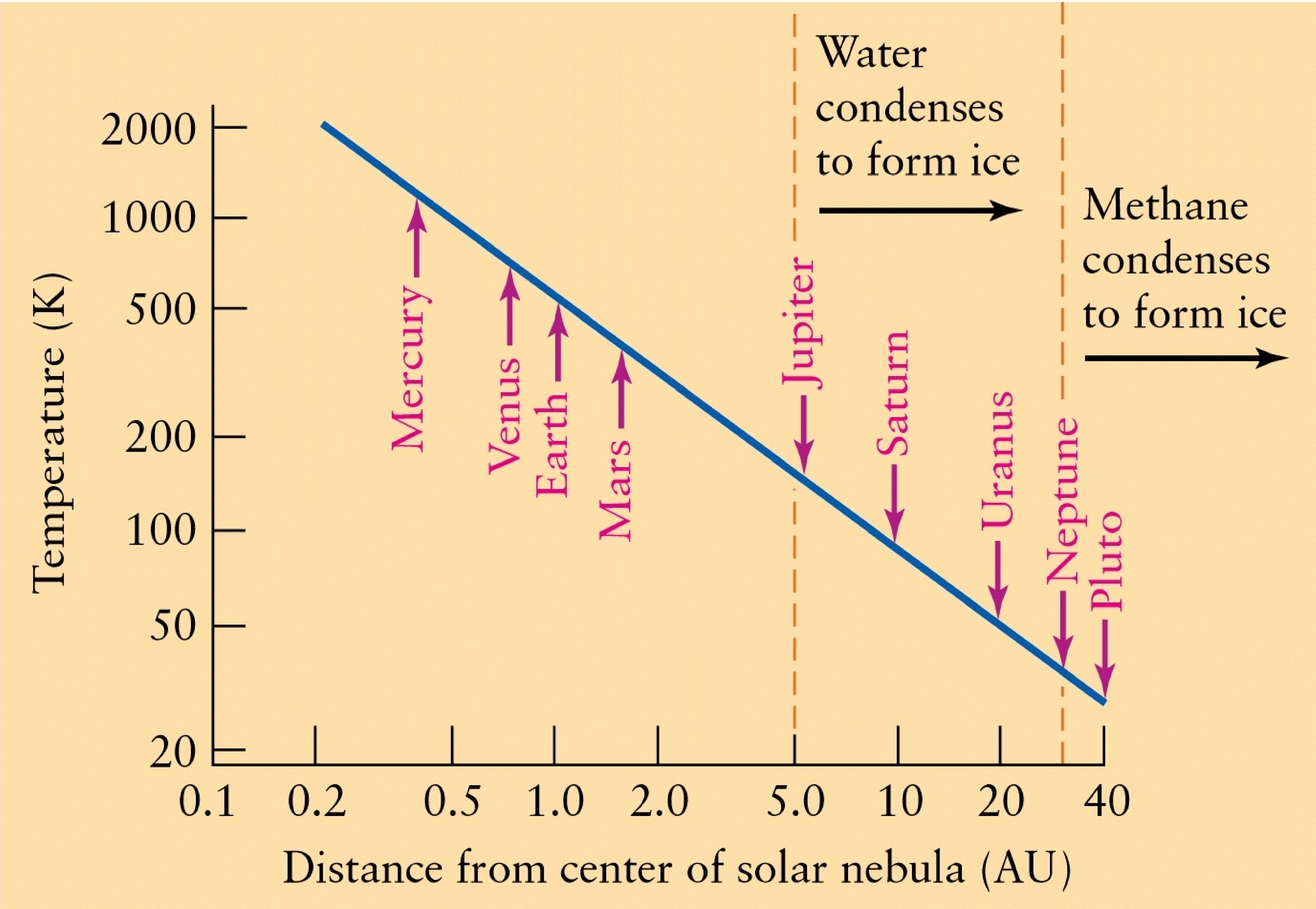
- ~75% H, ~23% He,
  2% everything else
  -How do we know?
  Meteorites
  (especially chondrites)
  versus
  Solar atmosphere



The protoplanetary accretion disk STRUCTURE

- A turbulent ACCRETION DISK
- Hotter near the star, cooler far away.
- Disk denser near star
- The 'snow line' or 'frost line' near the current distance of Jupiter (about 5 AU)

Temperature structure



The Lewis Model

- Chemical condensation sequence at low pressure
- As T drops, different chemical species can condense starting at 1600 K
  - Refractory Oxides and Metals first
  - then Silicates (<1200 K)
  - then water ice (<160 K)
  - then ammonia and methane ice (<100K)

Condensation sequence

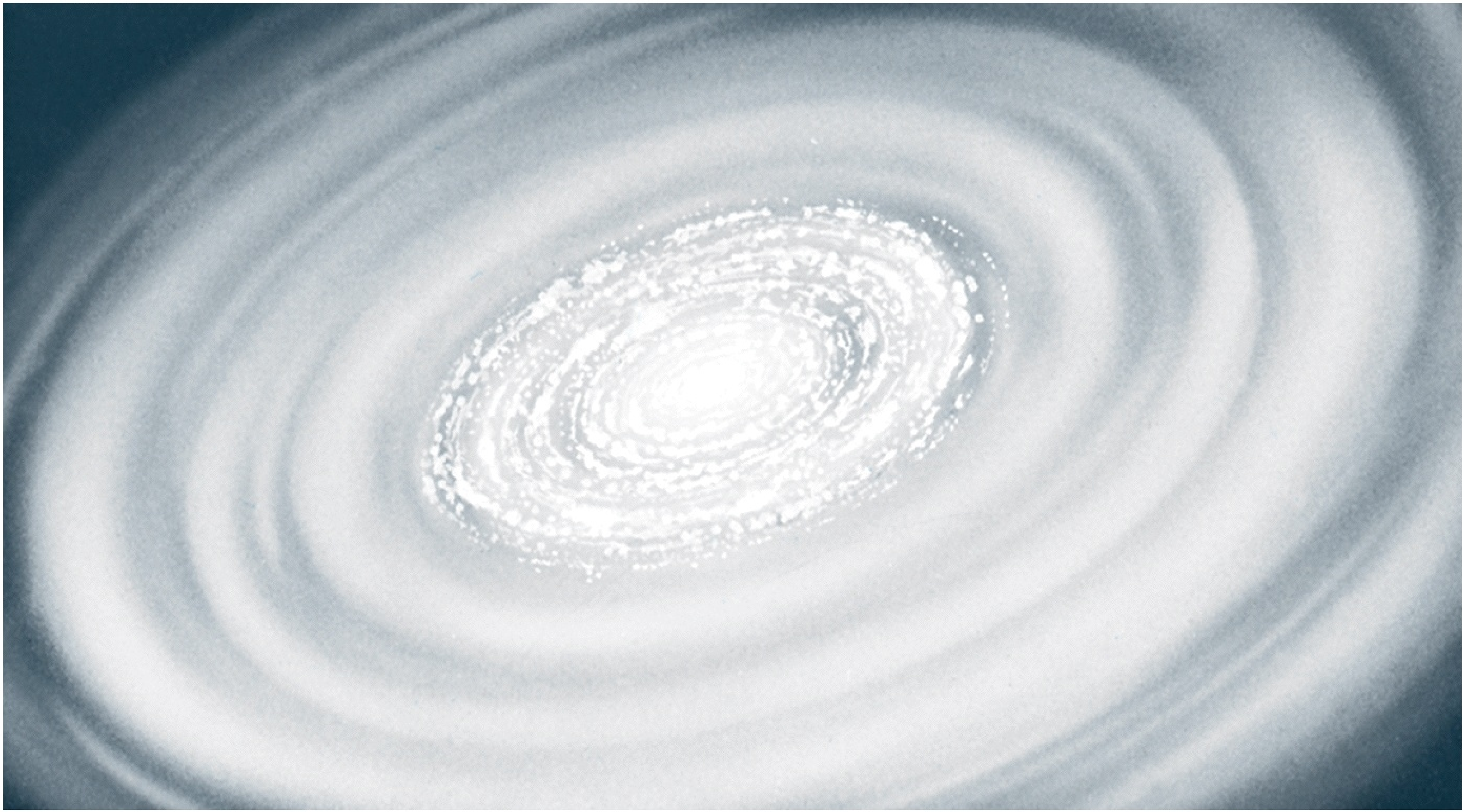
Table 9.1 Materials in the Solar Nebula A summary of the four types of materials present in the solar nebula, along with examples of each type and their typical condensation temperatures. The squares represent the relative proportions of each type (by mass).

	Metals	*Rock*	*Hydrogen Compounds*	*Hydrogen and Helium Gas*
				
Examples	iron, nickel, aluminum	various minerals	water (H_2O) methane (CH_4) ammonia (NH_3)	hydrogen, helium
Typical Condensation Temperature	1,000–1,600 K	500–1,300 K	<150 K	do not condense in nebula
Relative Abundance (by mass)	0.2%	0.4%	1.4%	98%

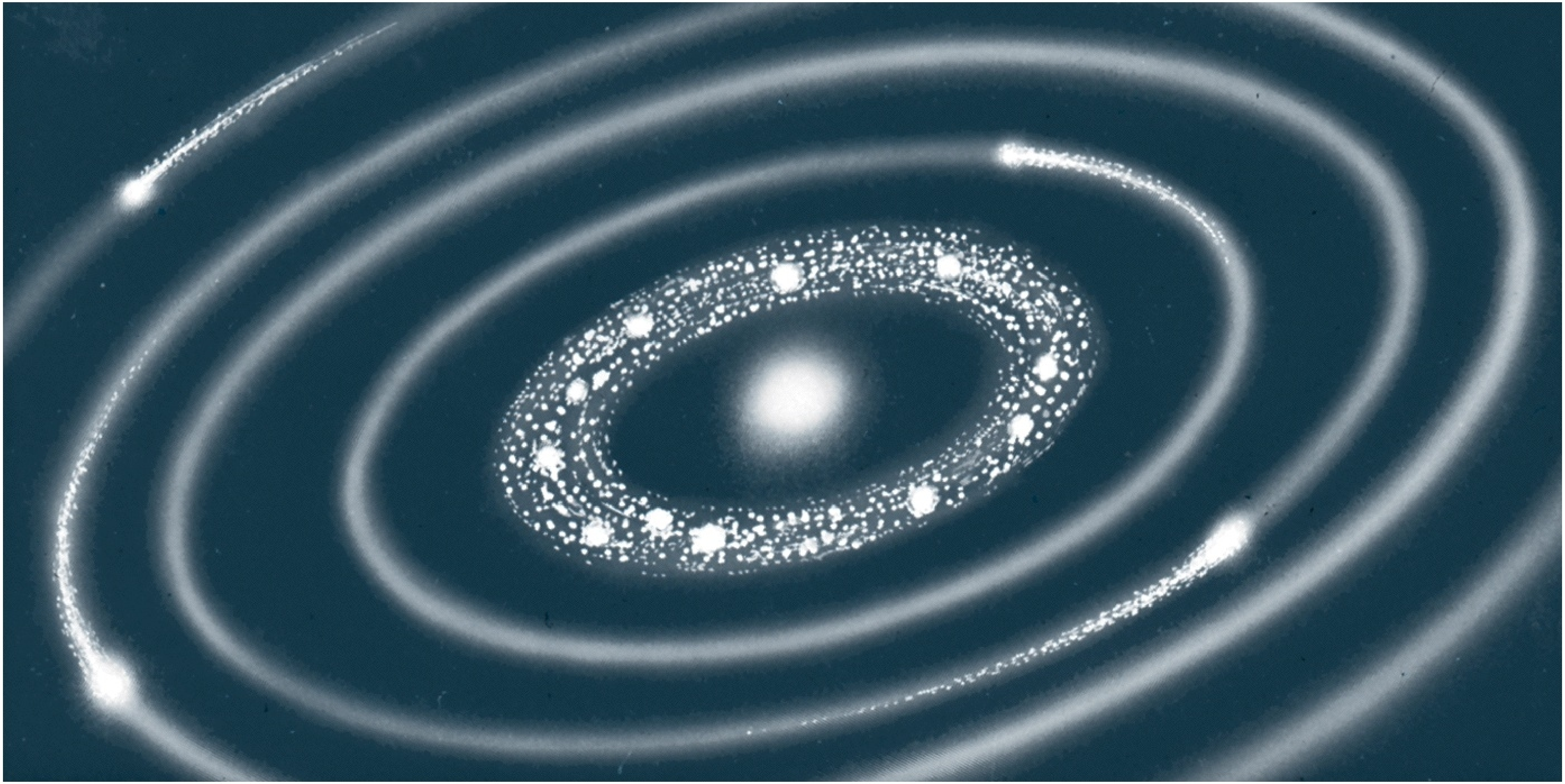
Lewis Model: Correct predictions

- Rocky bodies closer to Sun, icy bodies farther out
- Mercury: Large metal content
- Venus/Earth/Mars sequence of more water (bulk)
- 'Wet' asteroids in the outer main belt.
- Icy satellites of the giant planets

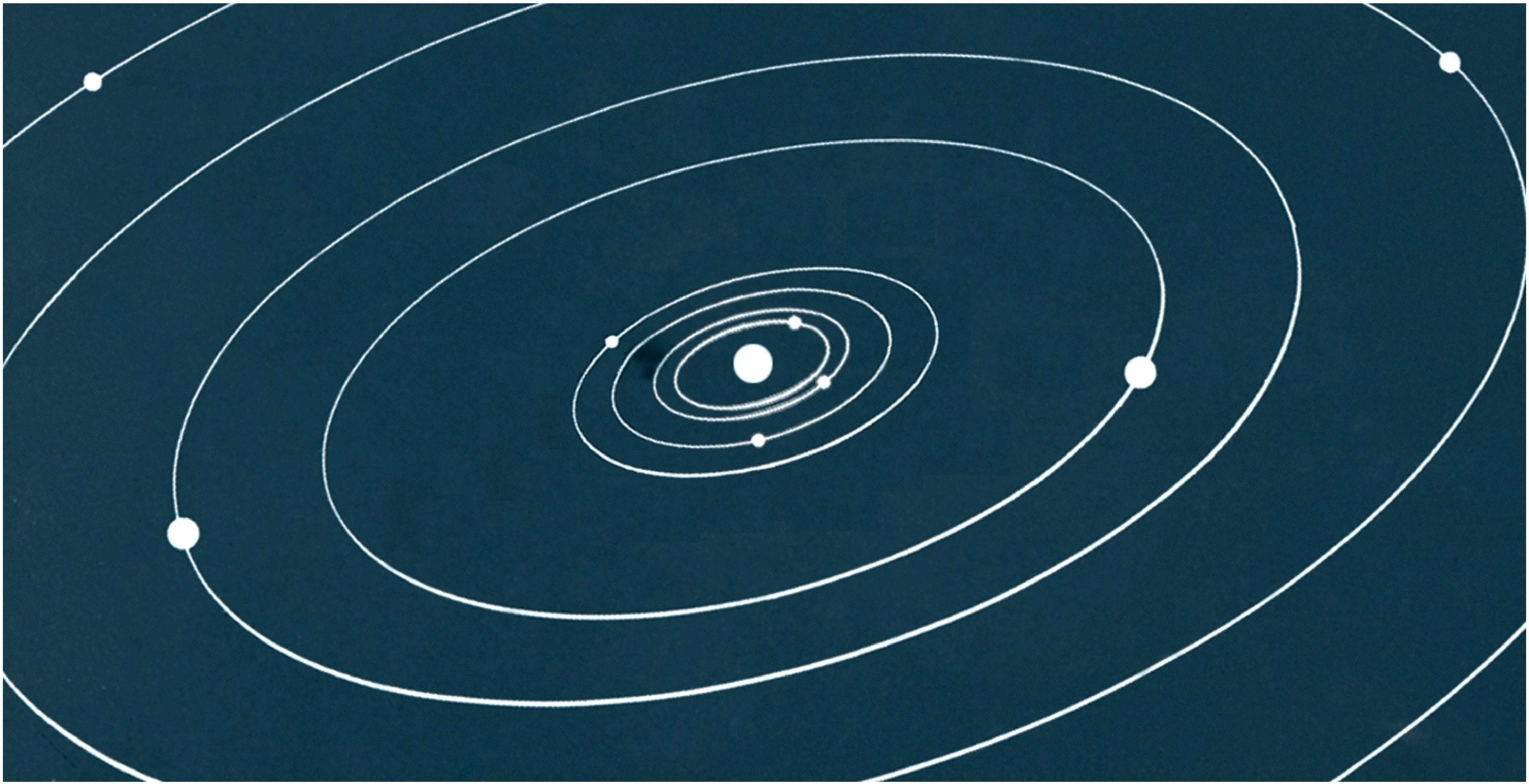
But how do you put planets together from dust???



First form small 'planetesimals', and they clump together to form planets (well, that's the theory...)

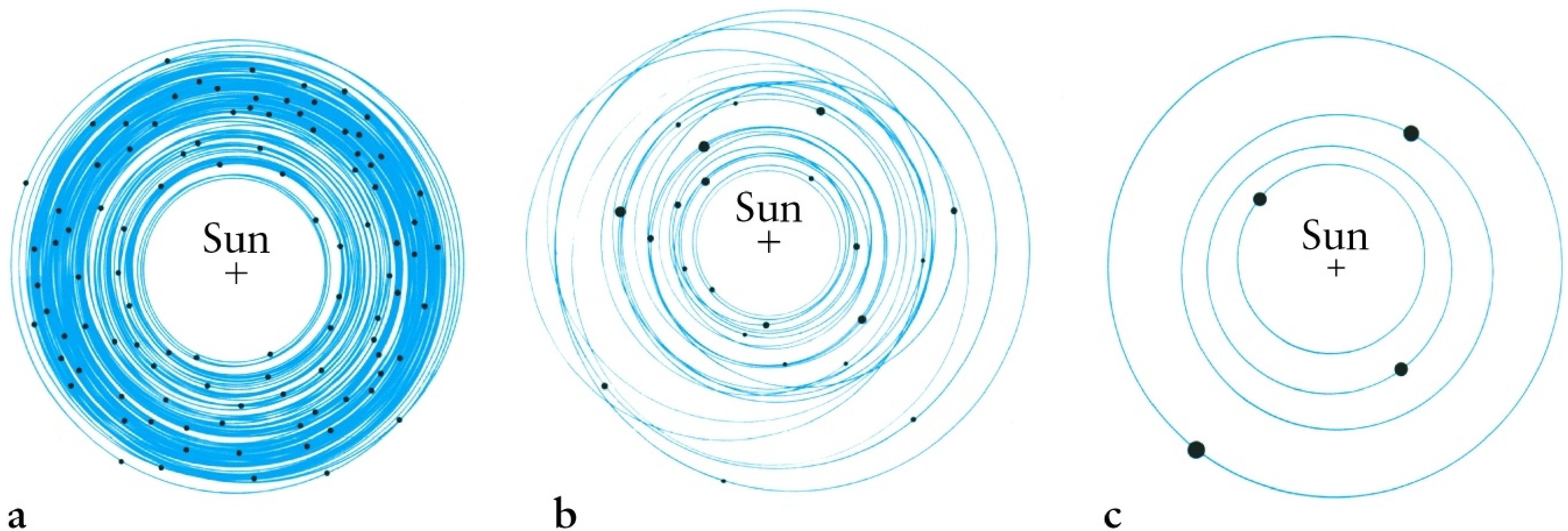


These planets, having formed in the spinning disk, have low e and i.



For the terrestrial planets, this can be successfully simulated on a computer. The planets form from planetesimals in about 100 Myr.

But doesn't work for the giant planets.



A Few Exceptions to the Rules…

- Both Uranus & Pluto are tilted on their sides.
- Venus rotates “backwards” (i.e. clockwise).
- Triton orbits Neptune “backwards.”
- Earth is the only terrestrial planet with a relatively large moon.