K8: The Basics of Planetary Atmosphere Formation

- Stars, solar systems form within giant molecular clouds
- Requires **high density**, **dust, and low temperatures** to initiate gravitational collapse
- Most material is hydrogen and helium; only a few percent is other elements
- Gravitational tugs from nearby stars cause infalling material to acquire angular momentum, settle into a disk of gas with some dust, and out of this forms planets
- The basics of what determines a planet’s atmosphere and how it keeps that atmosphere

To Get Planets, You Need Stars: Conditions for Star Formation…

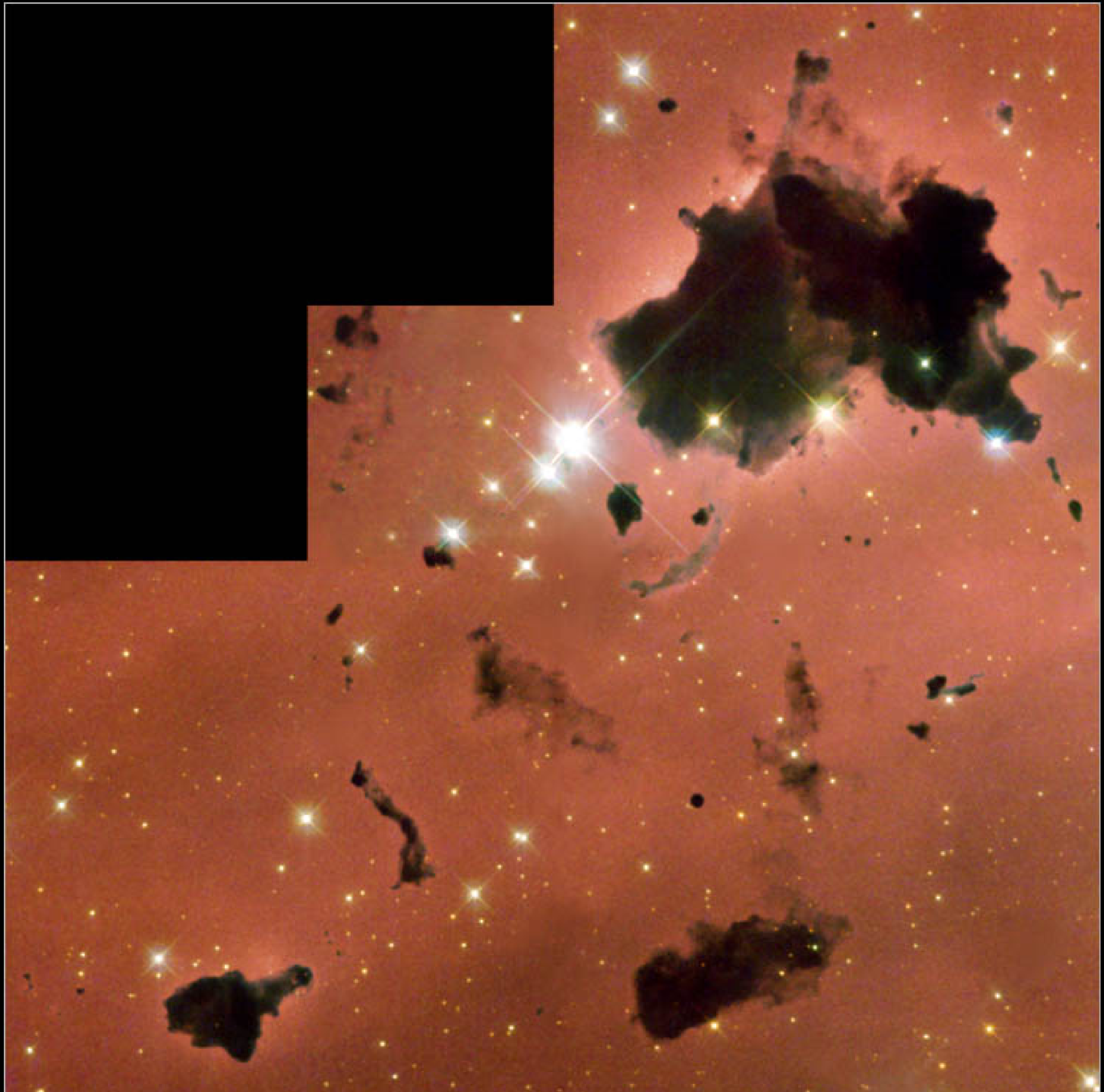
- Stars form in giant clouds of gas and dust
- Often called "Giant Molecular Clouds" because the conditions also favor formation of molecules like water, CO, CO2, etc.
- Need HIGH density areas
- Need COLD temperatures

Molecules Act as Coolants for Interstellar Clouds – Good!

- To get clouds to cool, you need molecules, which are good coolants because they transfer kinetic energy (i.e. temperature) of collisions into internal excitations which then de-excite into photon emission, and so the energy escapes from these extremely low density clouds (not so in Earth's lower atmosphere, so molecules are not always coolants – more on that later)
- Cold temperatures mean low pressure so gravity can cause the proto-star to collapse

And, Need some DUST

- Why? Because dust will block all hot radiation and keep the area cool. Your protostar doesn't like to be bombarded by high energy radiation from nearby stars!
- It likes to be inside a nice cold "dust cocoon", where it can slowly bring together the gas and dust via gravity, and make a star
- Cold dust not near stars, will be dark, silhouette'ing in the photos to come…



N11B in the Large Magellanic Cloud

Hubble Heritage

A Classic Hubble Photo of the Orion Nebula Star Formation Region…

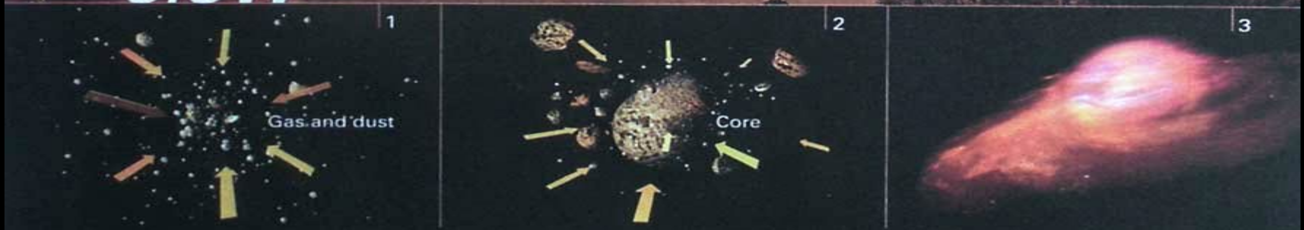
- The Orion Nebula is the nearest rich star formation region, with hundreds of new stars still forming
- Inside the Orion Nebula, we see new solar systems forming!
- We see proto-planetary dusty disks surrounding many newly forming stars
- The neighboring stars compete gravitationally for infalling material, so it can't fall STRAIGHT in, and hence you create **angular momentum**, and it is THIS material which remains outside the star and can collapse into planets.

How do the planets themselves form in this disk of dust and gas?

- Gravity mostly
- More detailed answer – is a very difficult computational problem, and only the basics are known about the detailed formation history of a given planet
- And – it's beyond the scope of this course. We'll just sketch it quickly
- See Astro 3 for a little more detail
- **Because in Astro 7 we are concerned with the atmospheres of planets and the physics that determines the properties of those atmospheres.**

birth theory

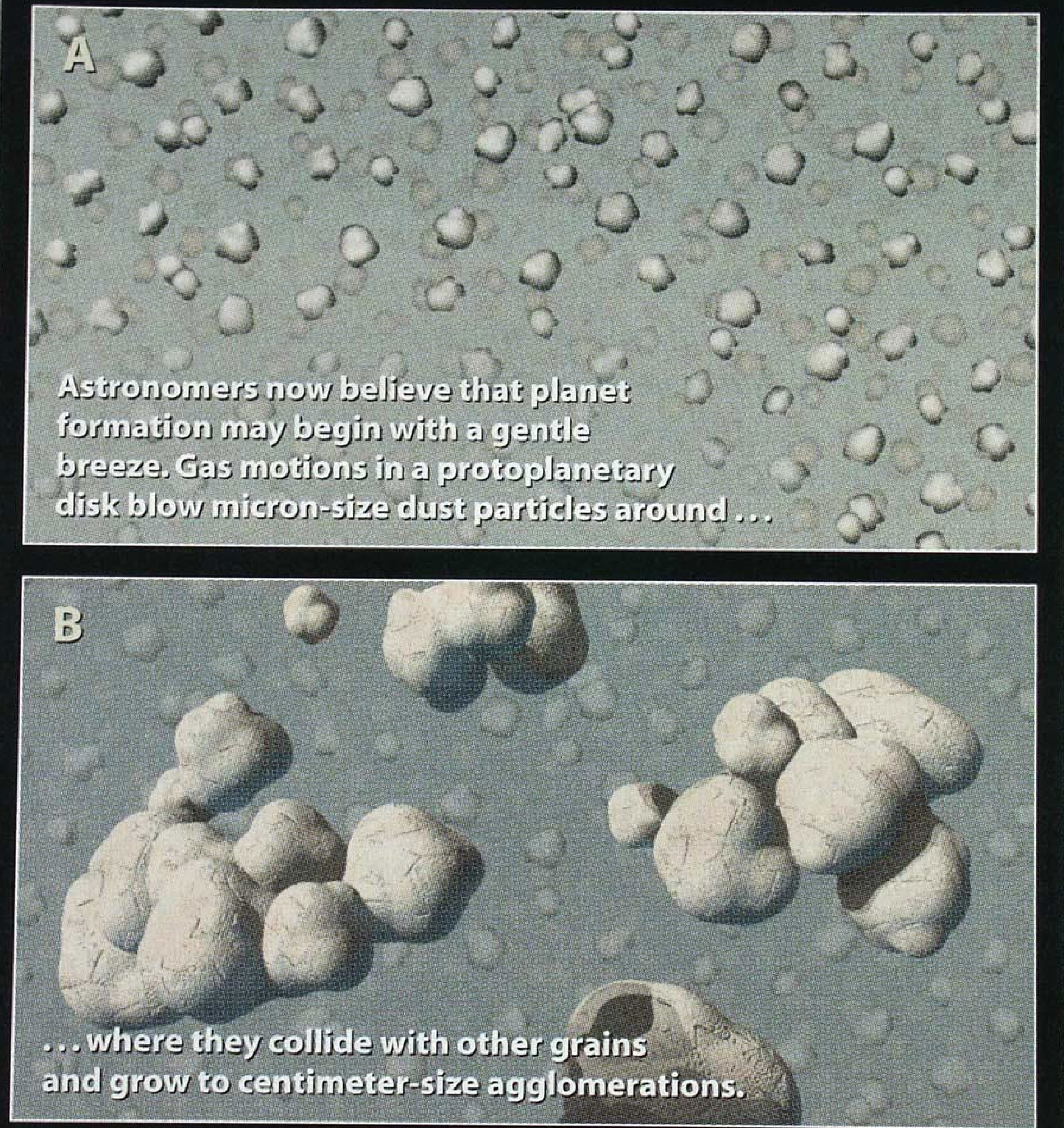
slow



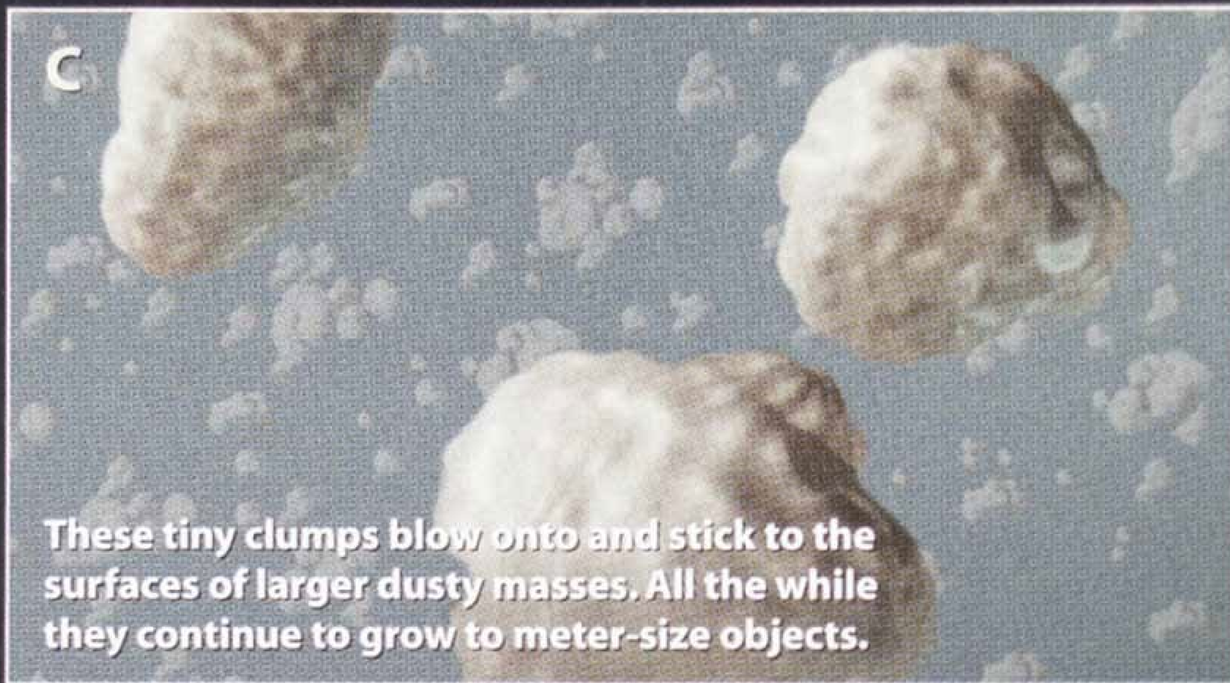
Core Accretion

The first planets to emerge from the whirling disk of gas and debris that surrounds a newborn star are gas giants like our Jupiter and Saturn. Most astronomers think they take shape slowly by growing step by step from the rocky material in the disk (top). First, tiny dust grains stick together (1), forming larger grains that collide to form still larger lumps. The growth process eventually yields solid cores roughly ten times the mass of the Earth (2). Their powerful gravity sucks in gas from the disk to create a giant, gas-cloaked planet (3).

Making a planet this way could take several million years. That's too slow, say some theorists, who argue that the gas needed for planet growth may not linger that long in the disk. They favor a fast alternative (facing page). Either way, smaller, Earth-size planets would form much later, from the leftover disk material.



Dust grains making "dust bunnies", through static electric charge separation caused by collisions.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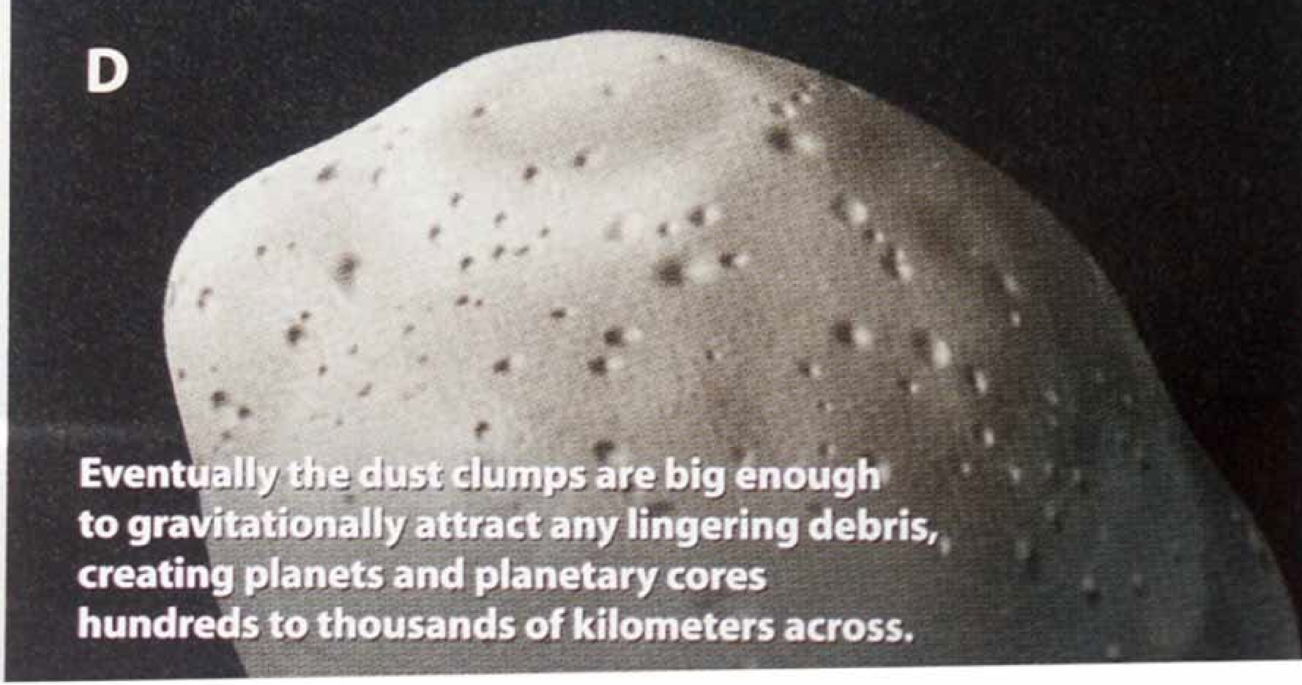
These tiny clumps blow onto and stick to the surfaces of larger dusty masses. All the while they continue to grow to meter-size objects.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Eventually the dust clumps are big enough to gravitationally attract any lingering debris, creating planets and planetary cores hundreds to thousands of kilometers across.

Inner Planet Formation…late in the process

The “Fast” Scenario; Eddy’s form of dust AND gas too, collapses to make a planet

- As the mass of the system gets concentrated into the central star, orbital speeds in close are fast, and farther out much slower
- This causes friction; differential rotation, and this generates eddys of spinning vortices
- These may run into each other and combine, eventually being large enough and dense enough to gravitationally collapse and make a planet
- **Why is this faster? Because these eddys have not just the rare dust, but the 50x more of gas, so gravity is a much stronger and faster process**

The "Fast" Scenario: Eddys of dust and gas collect into Proto-Planets, then merge into Planets

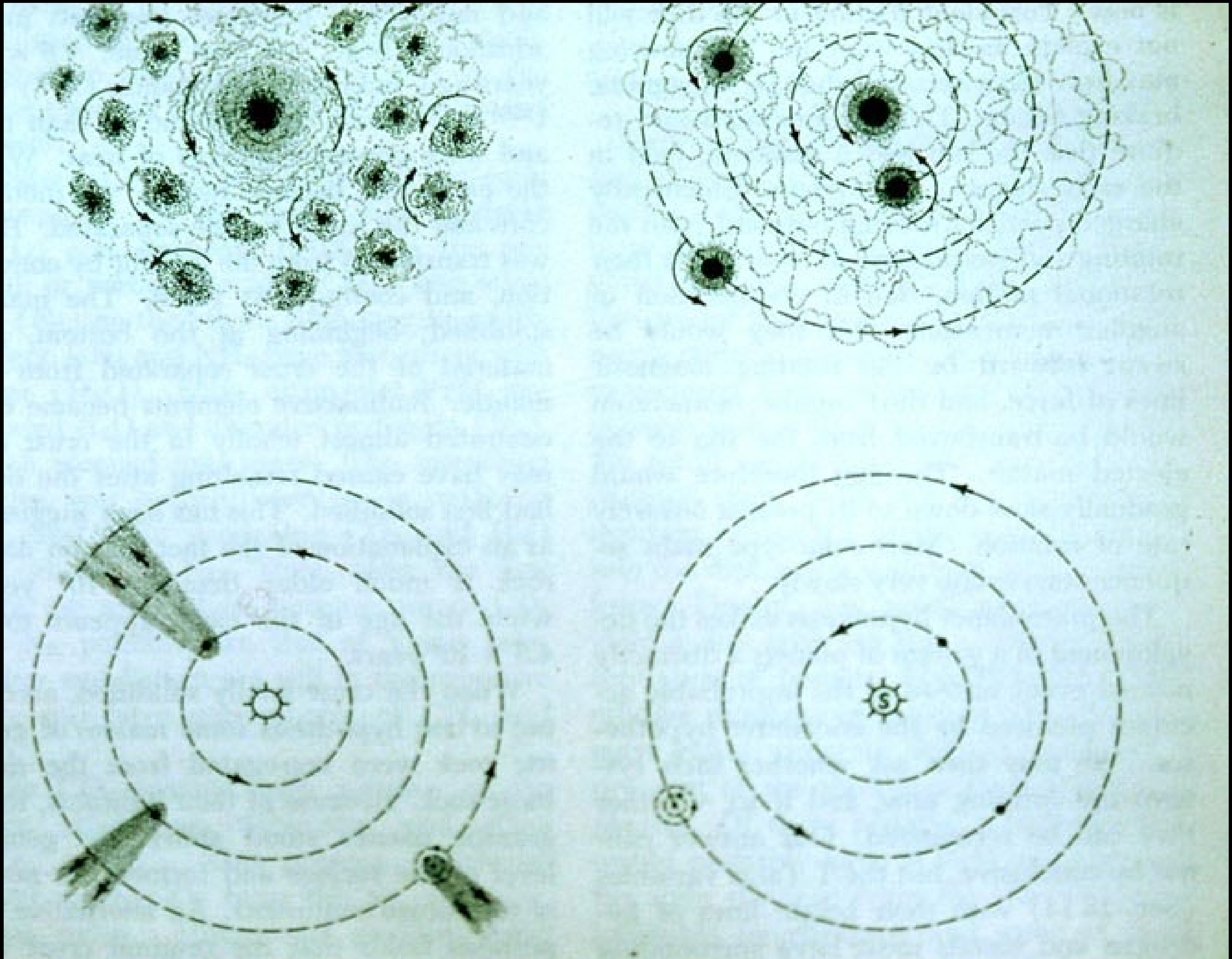
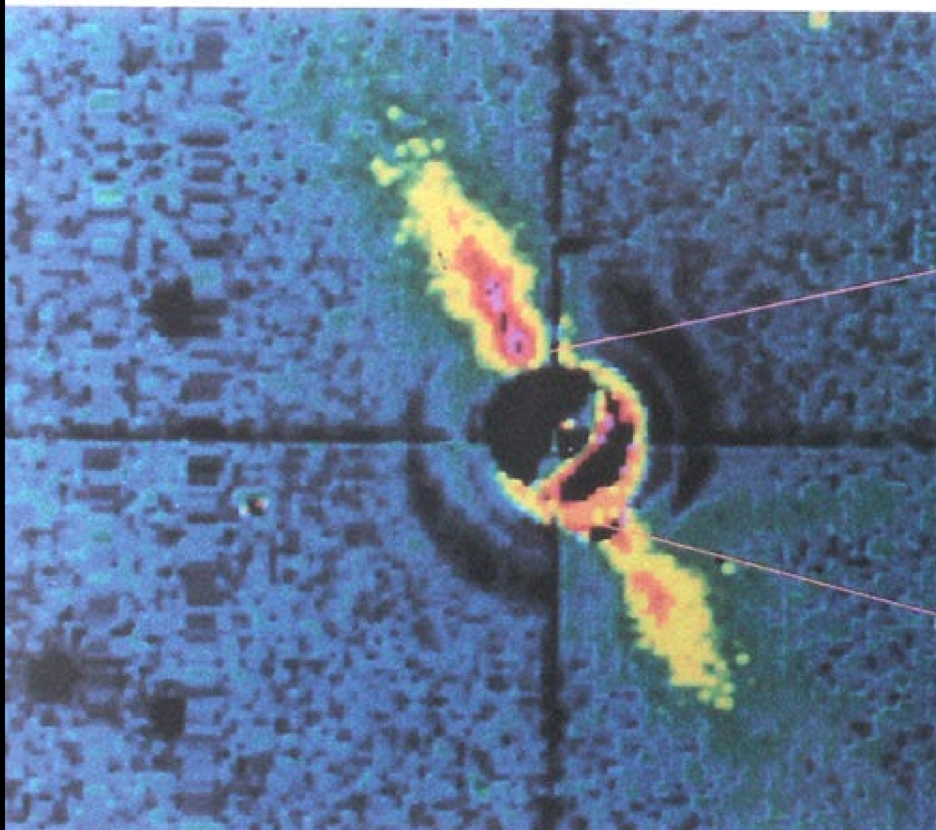


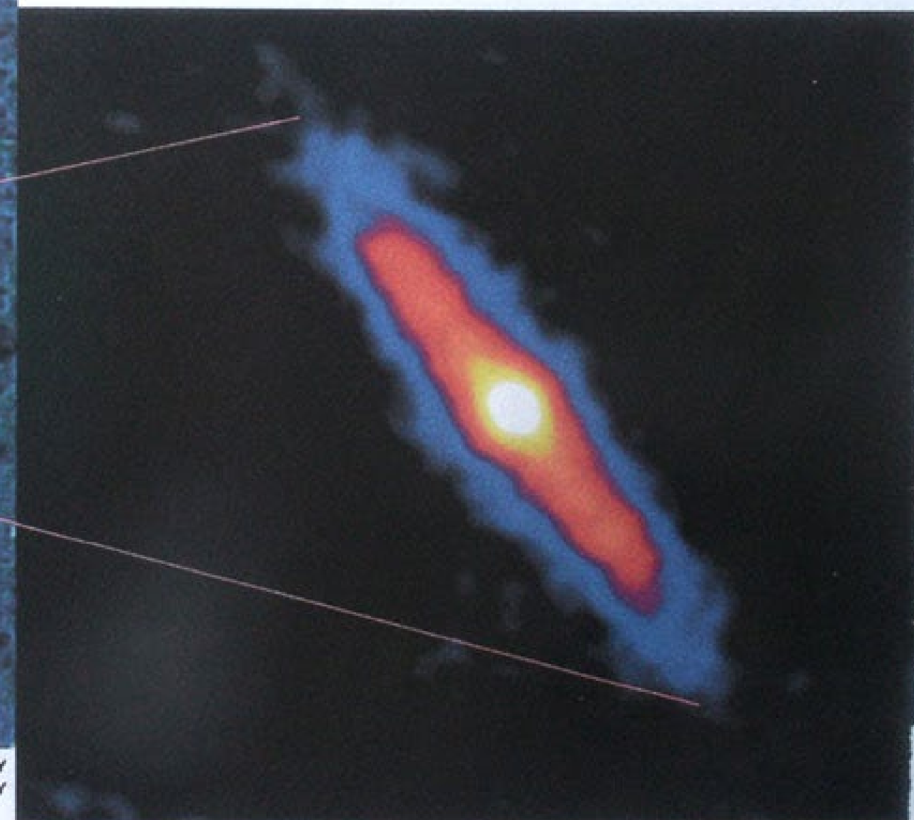
Figure 24.6 Origin of the solar system from a turbulent cloud of gas and dust, according to the protoplanet hypothesis.

Probably Both Processes Happen…

- **The inner solar system** was warm, near solar wind, hard to hang on to the gas for very long, so the "dust bunny" idea probably is what happened, resulting in rocky planets with almost no atmosphere
- **The outer solar system** was cold, far from the pressure of the solar wind, could hang on to their light gas elements (hydrogen, helium, methane, etc) and so made the Jovian Planets

A vast cloud of dust, perhaps kicked up by colliding asteroids, envelops the young star Beta Pictoris in images from 1984 (left) and last January. Both images give a side view of the disk-shaped cloud and indicate brightness with false color. The earlier one, made in visible light, reveals only the disk's edges, but the new infrared view homes in on a smaller region about twice the size of our planetary system. The part of the disk colored red looks lumpy, perhaps because unseen planets are displacing the dust.





BRADFORD SMITH, UNIVERSITY OF ARIZONA, AND RICHARD TERRILE, JET PROPULSION LABORATORY (ABOVE); CHARLES TELESCO, UNIVERSITY OF FLORIDA, AND SCOTT FISHER, GEMINI OBSERVATORY

What Halted the Process of Planet Formation? The Solar Wind

- Remember, photons of light have momentum
- When parent star "turns on", its luminosity blows away the gas dust cocoon around the star
- Then, the disk of gas and dust is also eventually blown away, so there is no more material to accrete onto the planets
- Takes a few million to a few 10's of millions of years

Any successful Solar System Formation theory must explain some key patterns…

- 1. All planets orbit in the same plane
- 2. All planets orbit in the same direction
- 3. All planets have nearly circular orbits
- 4. Planet orbits are non-intersecting

And – Our Story we've unfolded fits very well!

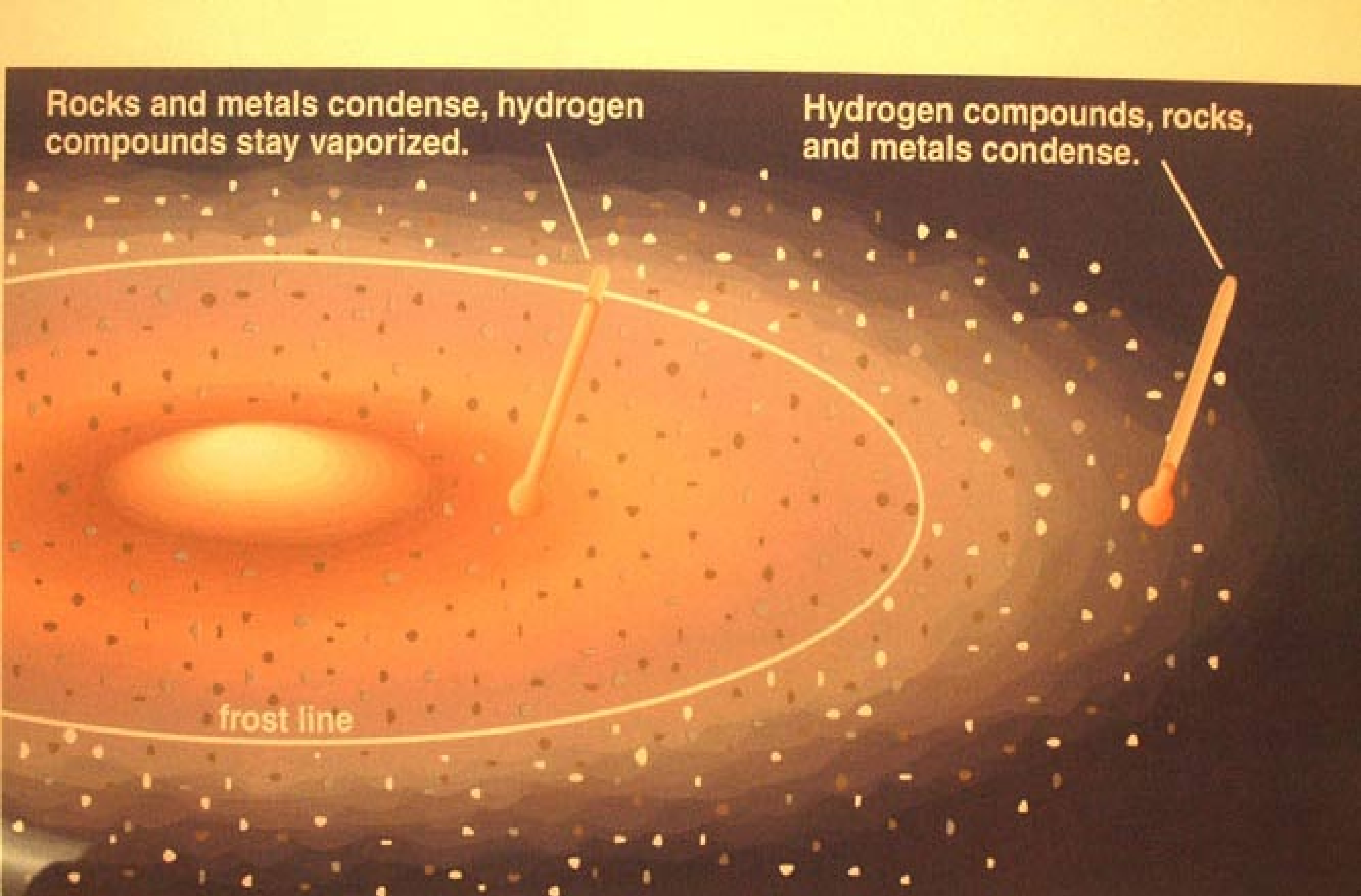
Some General Features of Our Solar System

- **The Inner planets** – Mercury, Venus, Earth, Mars
- -- small
- -- made almost completely of rock
- -- no natural moons or rings
- -- thin (or no) atmospheres, mostly of carbon dioxide (except Earth) or molecular nitrogen; these are **heavy** gases.

…Then the Asteroid belt

- ~ a million rocks or rock/ice boulders, up to a few hundred miles across
- The large majority orbit between Mars and Jupiter
- Probably formed from the collisional breakup of several small planets which had unstable orbits due to Jupiter's strong gravity nearby

The Frost Line



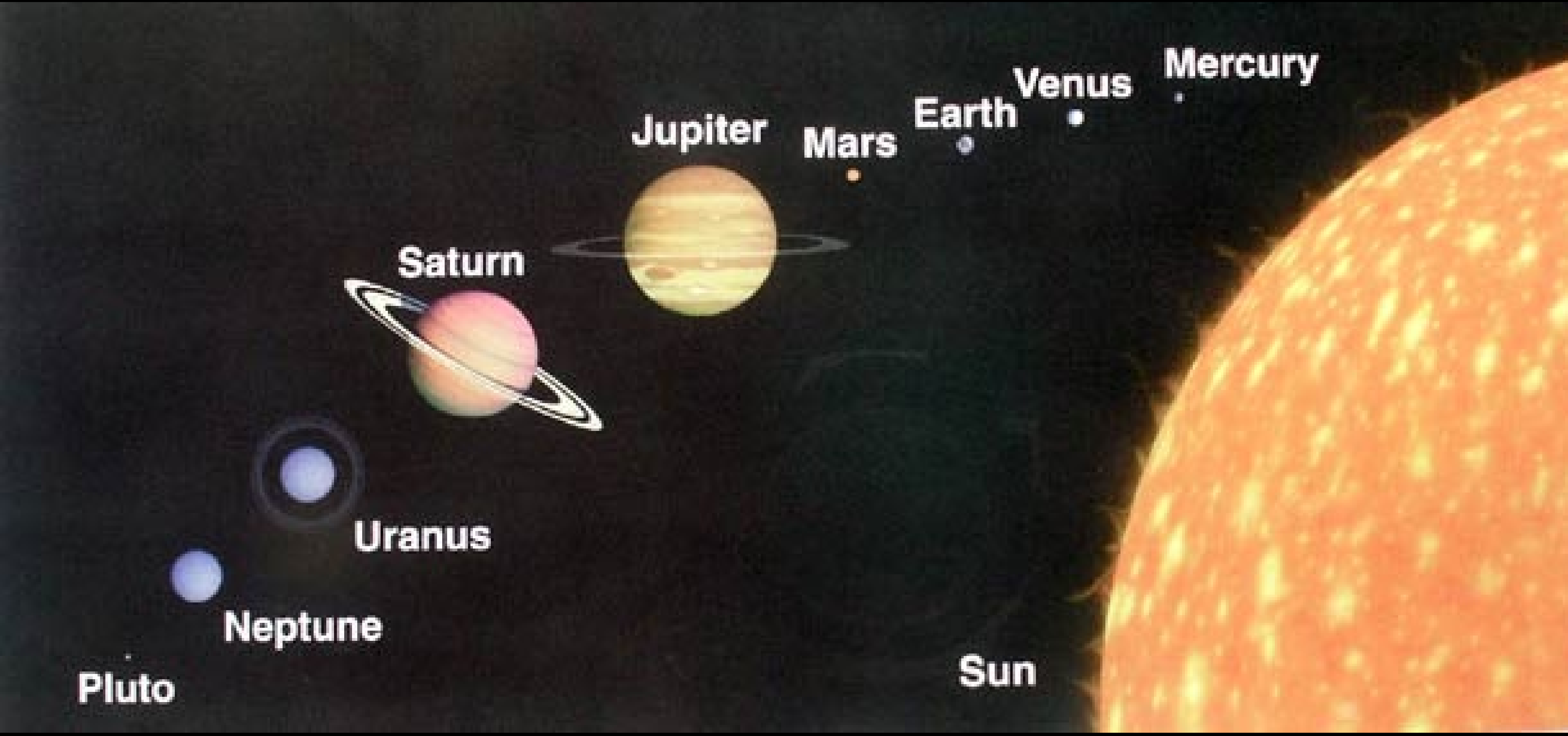
Beyond the Frost Line…

- Hydrogen compounds (mainly water) able to form snow flakes, then snow balls, and hang together to make self-gravitating proto planets
- Since hydrogen (H) is the vast majority of ALL the mass in the solar nebula disk, being able to hang on to H and He means MASSIVE planets beyond the Frost Line

the Outer Planets – Big and Massive

- Jupiter (2.5 times the mass of ALL other planets put together), with enough mass to make enough pressure to form liquid hydrogen, and rocky core at the bottom
- Saturn – small rocky core surrounded by a little liquid hydrogen and then deep layer of H and He
- Uranus and Neptune – smaller, small rock core and H, He envelope
- All have large natural moon systems
- All have rings of icy and/or dusty material

Our Planets (Pluto is a Kuiper Belt stand-in)

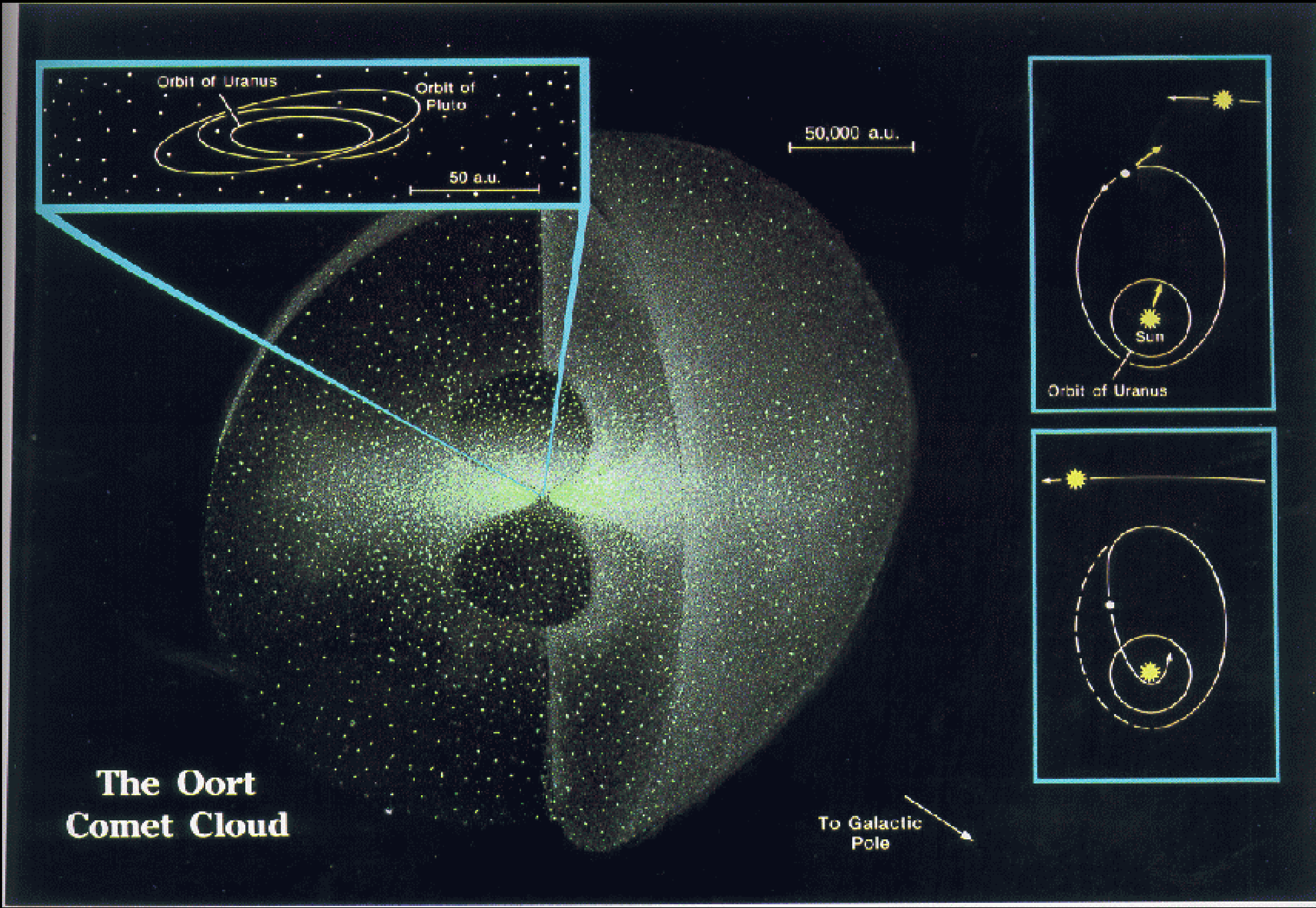


Beyond Neptune… the Kuiper Belt of Giant Ice Worlds

- Thousands or tens of thousands of balls of dirty ice up to a few hundred miles across.
- Possibly the remnant of a once much larger reservoir of icy objects which were scattered by planetary migrations of Uranus and Neptune
- Perhaps out here the solar nebula was too sparse and collisions were too rare to pull together material into large planets
- Pieces of these provide the comets that helped supply some of the water and light elements to the inner planets like Earth

Finally, 100 times farther still…

- The **Oort Cloud** of comets
- Inferred from the observed orbits of comets which have their farthest points vastly farther away than Pluto.
- About ½ light year from the sun – pretty much at the theoretical limit that objects can remain gravitationally bound to the sun for 5 billion years without getting tidally yanked off by other stars passing by.
- No flattened shape to the distribution of these objects – too little angular momentum to settle the material into a disk (or "belt"), so it's a roughly spherical "cloud"


Orbit of Uranus
Orbit of
Pluto
50 a.u.
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Sun
Orbit of Uranus
The Oort
Comet Cloud
To Galactic
Pole

How a Planet Retains an Atmosphere

- ***Surface gravity*** must be high enough and
- ***surface temperature*** must be low enough, that the atmosphere molecules don't leak away during the 4.6 billion years since formation.
- Outer (i.e. Jovian) planets are so distant and so cold, they formed from seeds of ices (water, ammonia, etc) and hydrogen compounds like this made up much higher fraction of the proto-solar disk than rocky dusty material
- Net Result: Jovians have much more atmosphere or (in Jupiter's case) liquid hydrogen

The three ways a planet loses atmosphere: First… <u>leakage</u>

Lighter molecules move faster, because on average ***Kinetic Energy is higher at higher temperatures***

- Recall $(½)\mathbf{m}\langle v^2\rangle = (3/2)\boldsymbol{k}T$ where **m** is the mass of the particle (atom or molecule) moving at velocity **v**, through a medium of temperature **T**
- For a given temperature, higher mass particles will have lower velocity, is what this equation is telling us. Think of elephants lumbering around, *vs.* hummingbirds
- Molecules are continually bouncing off of each other and changing their speed, but if the average speed is higher, the odds are higher that during the colliding, it may escape the planet's gravity.

Surface Gravity/Earth's, and escape velocity. High escape velocities for the outer planets allow them to retain light gases H2 and He

- Mercury = 0.37 and v_e = 4.3 km/sec
- Venus = 0.88 and v_e = 10.3 km/sec
- Earth = 1.00 and v_e = 11.2 km/sec
- Moon = 0.165 and v_e = 2.4 km/sec
- Mars = 0.38 and v_e = 5.0 km/sec
- **Jupiter = 2.64 and v_e = 59.5 km/sec**
- **Saturn = 1.15 and v_e = 35.6 km/sec**
- **Uranus = 1.17 and v_e = 21.2 km/sec**
- **Neptune = 1.18 and v_e = 23.6 km/sec**
- Pluto = 0.06 and v_e = 1.2 km/sec

So…. A slow leak. Like air from a pin-pricked bicycle tire

- **Hydrogen and Helium = 97%** of the mass of the solar nebula, and these are the lightest and **<u>easiest molecules to lose.</u>**
- ***But they are NOT lost by Jupiter, Saturn, and to a good extent Uranus and Neptune. Their mass is high, gravity is high, escape velocity is high, and temperature is low so molecular velocities, even H_2 and He, are also low – low enough to retain most of the H_2 and He***
- ***Heavy molecules like N2 and CO2 could even be retained by some moons and inner planets***

The Second way to lose atmosphere…

Impact Cratering: Big comets and asteroids hitting the planet will deposit a lot of kinetic energy which becomes heat, blowing off a significant amount of atmosphere all at once.

- This is not much of an issue for the outer planets, who have high gravity and very high atmosphere mass, so even a big impact is unlikely to unbind much atmosphere

The Third way to lose atmosphere: weak magnetic field

- A magnetic field will deflect incoming charged particles (the solar wind, and also cosmic rays) and prevent them from “sandblasting” away, bit by bit, the atoms and molecules in your atmosphere
- This is not an issue for the Jovian planets – they’ve all got strong magnetic fields, and born with huge atmospheres which could withstand a little “sand-blasting” by the solar wind in any case.

So the General Features the Atmospheres of Our Planets Would be Expected to have…

- Small inner planets close to the hot sun would have thin atmospheres made only of heavy molecules, like diatomic nitrogen and CO2
- The outer planets are massive and cold and so could hang on to thick atmospheres of the primordial gases that make up most of the universe – hydrogen and helium, and hydrogen compounds
- This is indeed what we see – the subject of our next presentations….

K8 – Basics of Planetary Atmospheres and their Formation: Key Points

- Inner planets – formed by rocky material inside "frost line"
- Outer planets – formed by hydrogen compound ices as "seeds", and since H is most of the proto-solar system's material, these planets are large
- Beyond, is Kuiper Belt of 10's of thousands of ice worlds a few hundred miles across or less
- 100x further away is the Oort Cloud, size limited by tidal forces from other stars in our Galaxy to about ½ light year outer radius, of more ice cores.
- The kinetic energy ($1/2\ mv^2$) of a particle is proportional to its temperature, which means at a given temperature in an atmosphere, light molecules move fast, heavy molecules move slow. This means the light atoms and molecules can "leak" away to space except in very cold and massive worlds – the Outer Planets
- The 3 mechanisms by which a planet may lose atmosphere: (1) leakage of light molecules if it's too hot or too little gravity. (2) Impact cratering is significant only for the inner planets (3) weak magnetic field can leave a planet exposed to the solar wind, which can "sand blast" away one's atmosphere – not an issue for the outer planets
- Hence, inner planet atmospheres are thin, dominated by heavy molecules N_2 and CO_2. Outer planets retain primordial abundances, so that's primarily light atoms hydrogen and helium, which dominate the mass of the universe.
- Planet formation halted by luminosity of parent star blowing away gas, dust disk