Astro 210

Lecture 23

March 12, 2018

Announcements

- **HW7 due online in PDF, Friday 5:00 pm**
- **Night Observing next week** – great weather for sure :¿
  Campus Observatory. Monday through Thursday 7–9pm
  bring **report form** available on Moodle
  take and submit **selfie** while there

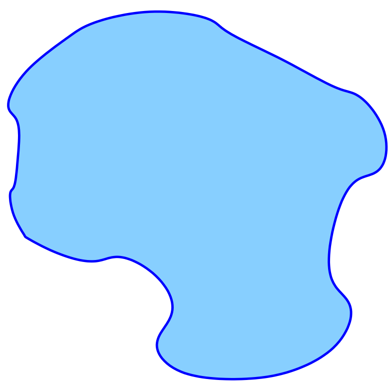
Theory of Solar System Origin: Protosolar Nebula

stars born in cold gas & dust clumps: molecular clouds
Q: what's dust, in astro context?
`www: HST Eagle Nebula`

Initial protosolar material a small parcel of larger cloud

- **cold gas & dust**
- **spinning**: net angular momentum $\neq 0$
  Q: why is $\vec{L} \neq 0$ a reasonable assumption?

First: imagine a cold cloud with *zero* spin
i.e., *zero* angular momentum



Q: forces on particles in cloud?
Q: response of particles to these forces?

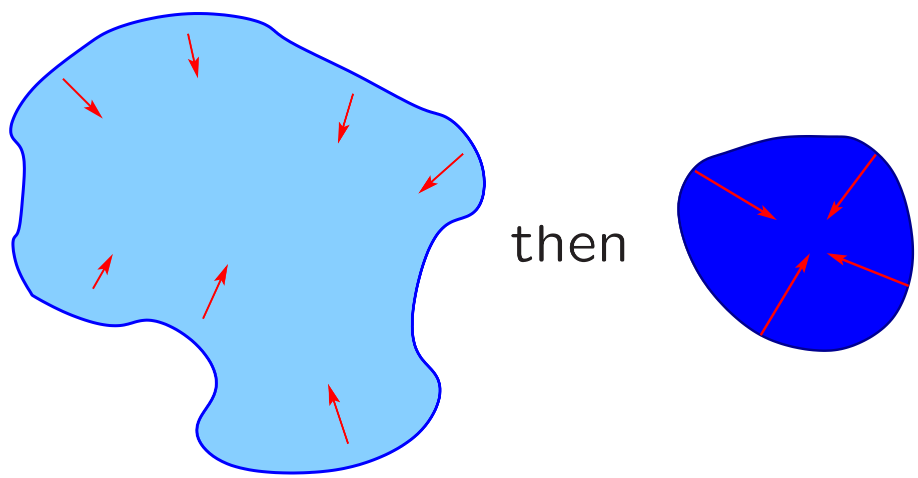
Q: why is coldness important for this to work?

Gravitational Collapse

ignoring spin:
particles in cold cloud feel forces of
- **gravity**
- **thermal pressure**

but if cloud is *cold:* T low, pressure $P = \rho kT/m_{\rm particle}$ small
$\longrightarrow$ *only important force is gravity*

gravity $\longrightarrow$ inward motion
$\longrightarrow$ denser
$\longrightarrow$ stronger gravity
$\longrightarrow$ runaway!
gravitational collapse



Q: why doesn't collapse continue until all matter $\rightarrow$ point?

iClicker Poll: Contraction of a Spinning Swarm

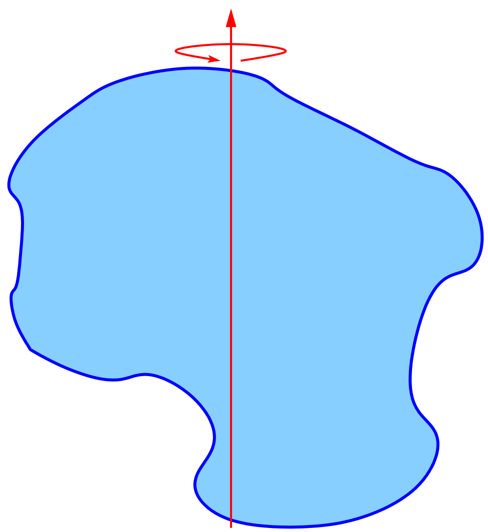
Consider a swarm of particles, spinning around an axis

Which is easier?

A moving a particle *parallel* to spin
$\downarrow$ toward midplane

B moving a particle *perpendicular* to spin
$\longleftarrow$ toward spin axis

C both motions equally easy



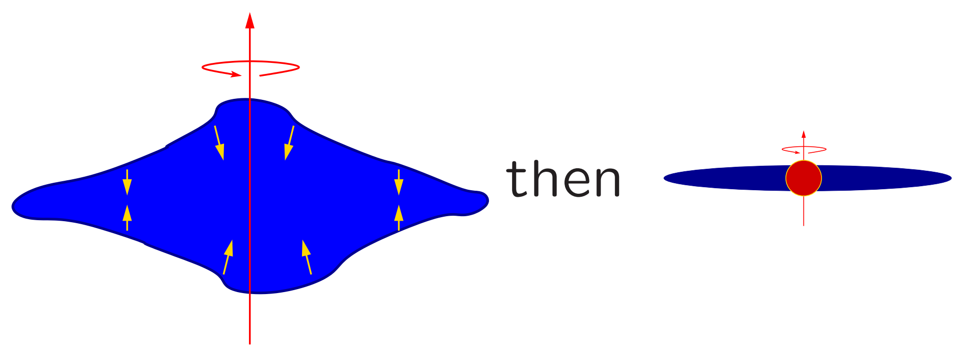
Nebular Collapse: Birth of Sun and Disk

in gravitational collapse: most matter $\longrightarrow$ central "proto-Sun"

but real pre-stellar clouds are clumpy parts of larger nebulae
$\longrightarrow$ turbulent motions
$\longrightarrow$ clumps have random but nonzero spins: $\vec{L}_{\rm init} \neq 0$

with $L > 0$: collapse is not spherical

angular momentum "centrifugal barrier"
resists motion toward spin axis
but not along spin axis
$\Rightarrow$ collapse easier along axis
$\Rightarrow$ protoplanetary disk



Q: consequences?

Disks Everywhere

disk formation is inevitable consequence of

- *gravitational collapse*
- *with nonzero angular momentum*

Twitter version:

Gravitational Collapse + Angular Momentum = Disks

Origin of

- spin of Sun
- disk = planet raw materials → all move in same direction
- ecliptic plane: traces original disk plane
- planet ingredients nearly coplanar: planet orbits nearly coplanar

Protoplanetary Disk

protosolar material with highest angular momentum
"spared" from going into Sun $\rightarrow$ remains as orbiting disk
disk ingredients: mostly H and He gas
with "sprinkle" ($\sim 2\%$ by mass) of microscopic dust
disk motion: feels gravity of proto-Sun
$\rightarrow$ moves in Keplerian orbits
non-circular velocity components $\rightarrow 0$
Q: why?

due to T drop with distance R from Sun:
gas ρ, matter state (presence of ices) varies with R
Q: how? what physical effects important for ice formation?

disk velocities: matter interactions occur
with non-circular (i.e., radial) velocity components
i.e., elliptical radial motions lead to collisions/heating: friction

- frictional drag forces drive radial motions to zero
- protosolar disk circularized $\rightarrow$ low-eccentricity planet orbits

temperature gradients and disk structure

hotter near (proto)Sun, cooler farther away

- higher gas presser closer: gas disk "puffier" nearby

what about solids? dust, ice?
key: condensation gas $\rightarrow$ solid

- rocks, metals $T_{\text{cond}} \sim 1000 - 2000$ K high!
- ice: $T_{\text{cond}} \sim 100 - 200$ K low!

∞ *Q: so what does this mean for what kinds of solids form where?*

The Snow Line

water/ice "snow" line at $R_{\rm snow} \sim 3$ AU:
Inner/Outer boundary!

- *inside $R_{\rm snow}$:* only dust (rocky material)
  can exist as a solid (no ices!): limited raw material
  $\rightarrow$ small, rocky planets formed there

- outside $R_{\rm snow}$: lighter elements (water, CO_2)
  can also exist as a solid (along with dust)
  $\rightarrow$ more raw material available $\rightarrow$ larger protoplanets

origin of Jovian/terrestrial composition differences!

Assembling the Planets: Challenges

Goal of Solar Nebula Theory:

- start with smooth, gas-dominated protosolar disk smoothly laced with with microscopic dust/ices
- explain physically-motivated steps leading to most of mass in planets, small remainder in debris and no remaining interplanetary gas

Q: how can small dust/ice particles interact?
Q: how would the particles clump and grow?

Growing Planets in the Protosolar Nebula: Gravity

gravity $\rightarrow$ everything attracts everything else

- advantages: "reaches out" over space
  democratic: affects gas and solids

- disadvantage: at the beginning, disk smooth, circular
  most gravitational forces due to Sun
  no large objects yet to pull in neighboring material

$\rightarrow$ gravity *is* crucial, *after* large objects exist
$\rightarrow$ but must first build objects over size "threshold"

Q: how can we do this with the ingredients at hand?

Growing Planets in the Protosolar Nebula: Sticky Rocks

collisions: dust particles tiny but numerous
collide with each other as cloud collapses

high-velocity collisions e.g., from head-on impacts
relative speed $v_{\rm rel} \sim v_{\rm orbit}$ violent!
release large energy $\rightarrow$ can destroy dust
negative progress!

Luckily: as disk circularizes, gas density grows
frictional drag forces strong: dust velocities $\rightarrow$ alignment

low-velocity collisions $v_{\rm rel} \ll v_{\rm orbit}$ – gentle!
solid particles stick! $\rightarrow$ make fewer, larger particles
  only effective in solids (dust/ice): not gas
  doesn't "reach out"–requires particles to touch
  initially dust/ice particles small–hard to "find" each other
$\rightarrow$ slow acting: collisional effects set planet formation time

Protosolar Choreography

Phase I: Collisional

solid particles (dust/ice) collide, stick

$\longrightarrow$ small solid bodies: "planetesimals"

(like asteroids/comets)

gas as yet unaffected

but acts as frictional drag on non-circular planetesimal motion

collisional processes continue until

planetesimals massive enough $\rightarrow$ gravity takes over

Phase II: Gravitational

big planetesimals attract small $\longrightarrow$ accumulate mass
$\longrightarrow$ even stronger gravitational sources
"the rich get richer"
$\longrightarrow$ fewer & larger objects: "protoplanets"

collisions $\longrightarrow$ spin tilts, craters, the Moon!

Q: once planetesimals/protoplanets gravitate effectively, how does the affect the gas in the disk?

Outer Solar System (beyond snow line):
when core $\sim 10 M_{\text{Earth}}$
gravity attracts, holds H, He gas
mass grows even more rapidly

Inner Solar System (inside snow line)
smaller cores (no ices), higher $T \rightarrow$ can't hold H, He
masses remain small

leftover planetesimals:

- rocky: asteroid belt
  Jupiter's gravity prevents planet formation
- icy: Kuiper belt, some ejected to Oort cloud

as proto-Sun brightens: remaining interplanetary gas heats
$\rightarrow$ if not captured by giant planets, then driven out of SS

Theory of Solar System Origin: Executive Summary

stars born in cold gas & dust clumps: molecular clouds
"gravitational collapse": runaway contraction

angular momentum: centrifugal barrier to collapse
most matter $\rightarrow$ proto-Sun
high-angular momentum matter: protoplanetary disk around sun

gas ρ, matter state (presence of ices) change with R
water/ice "snow" line at $R_{\text{snow}} \sim 3$ AU:
Inner/Outer planet boundary!

Testing Solar System Origin

until recently, Solar Nebula theory
had only one system to explain: us!

Now: Major new info on planet existence, birth
around other stars

Q: what questions can only be answered by looking elsewhere?

Q: what questions can't be answered by looking elsewhere?

Q: what observable predictions does Solar Nebula theory make for young stars, mature planet-bearing stars?

Testing Solar Nebula Theory

Now seeing planets, planet formation around other stars
Solar Nebula theory should work generally
$\longrightarrow$ should apply to these systems too
...though some details might vary *Q: why?*

General Predictions of Solar Nebula Theory

In forming stars (protostars):
1. young protostars have gas disk
2. older protostars have planetesimal disk

In fully-formed star and planet systems:
1. small planets near star
2. massive planets farther away
3. orbits nearly circular

Problem: solar nebula theory built to explain
one data point (SS)! $\rightarrow$ is the model "fine–tuned"?