Astro 210
Lecture 24
March 16, 2011

Announcements

- HW7 available, due next time
- office hours–me: after class; TA: 10:30-11:30 tomorrow
- Night Observing: **last chance** this week!
  if tonight is clear, it will be *last* session
  due to time change, hours now **8–10 pm**
  report forms, info online

Last time: started origin of solar system

- starting point: molecular cloud *Q: what's that? ingredients?*
- gravitational collapse *Q: what's that?*

Today: from collapse to planets

Nebular Collapse: Birth of Sun and Disk

in gravitational collapse
most matter compressed $\rightarrow$ central "proto-Sun"

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

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

disk $\rightarrow$ planet & debris orbit planes, spin axes

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) change 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?

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

- $< R_{\text{snow}}$: only dust (rocky material) can exist as a solid (no ice): limited raw material
  $\rightarrow$ small, rocky planets formed there
- $> R_{\text{snow}}$: lighter elements (water, CO_2) can also exist as a solid (along with dust)
  $\rightarrow$ more raw material available $\rightarrow$ larger protoplanets

$\Rightarrow$ origin of Jovian/terrestrial composition differences!

iClicker Poll: Fossils of the Protosolar Nebula

Which is/are "fossil(s)" of solar nebula disk formation?

A all planets orbit planes are close to ecliptic plane

B all planets move in the same direction

C Venus spin is retrograde $\uparrow_{\text{orbit}} \downarrow_{\text{spin}}$

D both (a) and (b)

E all of (a), (b), and (c)

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?

Forces/Interactions in the Protosolar Nebula

• gravity → everything attracts everything else
  advantages: "reaches out" over space
    democratic: affects gas and solids
  but: at the beginning, disk smooth, circular
  most gravitational forces due to Sun
  no large objects yet to pull in neighboring material
→ gravity will be crucial, but need large objects first
→ must cross minimize size "threshold" first

• collisional/sticking forces–atomic/solid state forces in solids
solid particles collide, stick → 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
→ slow acting: collisional effects set planet formation time

Protosolar Choreography

Phase I: Collisional

solid particles (dust/ice) collide, stick

$\rightarrow$ 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 $\rightarrow$ accumulate mass
$\rightarrow$ even stronger gravitational sources
"the rich get richer"
$\rightarrow$ fewer & larger objects: "protoplanets"

collisions $\rightarrow$ 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
→ 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)! → is the model "fine–tuned"?