Astro 210
Lecture 24
October 22, 2010

Announcements
- HW 7 due
- Night Observing finished, report due
- good news: no new homework for next week
  bad news: Hour Exam 2 next week
  similar setup, format, as last exam
  `www: exam info page`

Last time: began theory of solar system origin
- starting point: "protosolar nebula"
  Q: what's protosolar? what's a nebula?
- gravitational collapse *Q: what's that?*
- angular momentum and disk formation *Q: how does this work?*

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)

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 $R_{\mathsf{snow}} \sim 3$ AU:
Inner/Outer planet boundary!

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: what are available forces/influences?

Q: which would be the first to act?
which is most efficient in collecting mass into large bodies?

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 this affect the gas in the disk?

Q: what are effects as proto-Sun turns on and becomes bright?

Outer Solar System (beyond snow line where ices exist):
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

Result: inner rocky planets, outer gas giants, debris!

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
$\rightarrow$ 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"?

iClicker Twofer: Bets on Planet Formation

Vote your conscience!

Which prediction seem most solid to you?

A young protostars have gas disk

B older protostars have planetesimal disk

C small planets near star

D massive planets farther away

E planet orbits nearly circular

In same list: which prediction seems least solid?

Test I: Young Stars

evidence from direct imaging:
50% – 90% of youngest stars surrounded by gas disk
disks are common and perhaps unavoidable!

`www: Orion HST montage`
`www: protoplanetary disks in Orion`
`www: Orion disks set of 4`
`www: Orion disks side view (really disks)`

disks thick, blocks light
→ enough material to make planets
→ agrees with Solar Nebula theory!

→ good evidence for disk formation!

Debris Disks

Some older protostars and fully-formed have spectrum that has two peaks $\rightarrow$ two temperatures

- optical emission from the hot surface of star, and
- infrared emission from dust in disk!

Recently (past decade): can image the disks in the infrared

`www:` β `Pic disk w/star`

We see warm dust (but no gas)

- most emission from numerous small particles
- but probably much larger particles present
  some ambiguous evidence for this already
  ▷ lumpy, non-symmetric disks seen
  β Pic disk warped $\rightarrow$ due to planet gravity
- recently: giant planet **imaged** around βPic!

Solar Nebula Scorecard: Midterm Grades

General Predictions of Solar Nebula Theory

In forming stars (protostars):

1. young protostars have gas disk? **check!**
2. older protostars and fully formed stars have particle-bearing disk? **check!**

Solar Nebula Theory status:

Woo hoo! so far so good!

theory works up through disk formation

how about planets themselves?