Astro 210

Lecture 25

March 18, 2011

Announcements

- HW7 due
- Good news: no homework due after break
- Bad news: Hour Exam 2 Friday April 2

  `www: info online`

Last time: **Protosolar Nebula** theory for solar system origin

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 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"?

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 → 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 → 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?

recall Solar Nebula predictions:

- giant planets far from stars
- rocky planets close in
- orbits nearly circular

Test II: Exoplanets

Exoplanets = extra-solar planets = planets around other stars
⋆ have been sought for centuries!
⋆ first positive, definitive detection: 1994 (around dead star)
⋆ first detection around normal star: 1995

What took so long?
Exoplanet detection is a huge technical challenge
Q: Why?

Q: possible workarounds?

Challenges for Planet Hunters

Can't "just look" – glare!
feeble light from planet drowned out by star flux
$\rightarrow$ need a more clever workaround

Several detection techniques have been proposed
three of these have already borne planetary fruit!

Successful strategies thus far involve:
- look for planet(s) effect on host star
- get lucky
- both of the above

Planet Effects on Host Stars: Reflex Motion

recall Newton III: since star exerts gravity force on planet
planet *must* exert *same* force on star!

- *both* must accelerate! the star moves ("reflex motion")
  ...but $a = F/m \rightarrow a_\star \ll a_{\rm planet}$
- both stars and planet orbit fixed "center of mass"

thus:

- the star moves too!
- what remains fixed is the center of mass
  a point on the line connecting the star and planet

consider two objects of equal masses $m_1 = m_2$
Q: where is center of mass?
Q: how do distances r_1, r_2 to COM compare?

Center of Mass Reminder

Newton II: $a \propto F/m$

$+$ Newton III: $F_{p\,on\,\star} = -F_{\star\,\mathrm{on\,p}}$

$\Rightarrow$ F magnitude same, heavier object accelerated less

$\Rightarrow$ star moves slower, nearer to COM

• distances to center of mass:

total star-planet distance: $r_\star + r_\mathrm{p} = a$

and $m_\star r_\star = m_\mathrm{p} r_\mathrm{p}$

so: $r_\star / r_\mathrm{p} = m_\mathrm{p}/m_\star \ll 1$

$\Rightarrow$ and so $v_\star \ll v_p$ but $\neq 0$!

How to use this?

• in practice, can't track star orbit path – too small on sky

• but can look for "wobble" in star speed

1995: detection!

Planet Detection by Good Luck: Transits

if very lucky, planet orbit plane seen edge-on
so planet sometimes passes in front of star
⋆ causes partial eclipse of host star!
⋆ star dimming small but observable

Strategy: monitor light from candidate stars
look for brightness changes
as planet crosses ("transits") star's disk

Q: What is expected "light curve" of flux $F(t)$ vs time t?
Q: How to verify signal was due to a planet?
Q: How to use signal to learn about planet?

Extra-Solar Planets: Results to Date

as of today:

- 538 exoplanets, 449 planetary systems
  gg # in solar system!
- 493 planets found via reflex motion
- of these, 177 found via transits
  ...but *Kepler* is monitoring $>$ 1200 transit candidates!
- 21 planets found by direct imaging

What have we learned?

Getting the most from observable reflex motion

1. measure star P = planet P

Q: if I know the period, can I get more?

Exoplanet Properties: Decoding the Wobble

Exoplanet Observable: 1. Wobble Period P

Kepler, Newton: $a^3 = k(m_\star + m_p)P^2$ (HW: put in k and solve)

$\Rightarrow$ planet semi-major axis a!

`www: exoplanet census plot`

note power of Kepler's laws: get distance
without measuring directly, but just by studying wobble cycle

2. measure max wobble speed $v_\star$

Q: what does this tell us?

Exoplanet Observable: 2. Wobble Amplitude $v_\star$

wobble speed $v_\star \to$ planet mass

how? $v_\star =$ speed of star w.r.t. COM

diagram: star, planet speeds

$\vec{R}_{\rm CM} = m_p/(m_p + m_\star)\vec{r}_p + m_\star/(m_p + m_\star)\vec{r}_\star = 0$, $r = r_p + r_\star$

$m_\star v_\star = m_p v_p$ mom. cons.

COM formulae $\to m_p$

Note: planet orbit plane can be tilted w.r.t. sky

Q: if so, how is observed $v_\star$ affected?

Q: if so, is planet mass overestimated or underestimated?

`www: exoplanet mass data`

Q: what is typical mass found so far? is this a surprise?

3. measure wobble speed pattern versus time

Q: what does this tell us?

Exoplanet Observable: 3. Wobble Change vs Time $v_\star(t)$

orbit eccentricity from shape of $v_\star$ vs t

if circular $\to$ perfect sinusoid

if eccentric: not sinusoidal

Q: recall Keplerian speed behavior–what's $v(t)$ for high e?

`www: 51 Peg Doppler curve, e=0.014`

`www: 16 Cyg Doppler curve, e=0.67`

`www: HD 860606, e=0.92! Found in 2001!`

at least $4M_J$, goes from ~ 0.9 AU to 0.04 AU!

$\to$ range from 0 to 0.935!

not clear how to manage this!