Astro 210

Lecture 25

March 16, 2018

Announcements

- **HW7 due online in PDF, Friday 5:00 pm**
- good news: now new homework after break
- bad news: **Hour Exam 2** Friday after break:
  March 30, in class, info will be posted on Moodle
- **Night Observing one** *last chance after break*
  first clear night will be final opportunity
  due date extended to March 30

iClicker Poll: The Astro Grind

A famous person said:

“Astronomers choose units to keep away physicist riff-raff”

Vote you conscience!

How much of Astronomy (e.g., HW) is unit conversion?

A 10-20%

B 21-40%

C 41-60%

D 61-80%

E 81-100%

Extra-Solar Planets: Counts to Date

as of today:

- 3743 exoplanets
- 2796 planetary systems, 625 multiple planet systems
- 493 planets found via reflex motion
- NASA *Kepler* has found most: transit factory!

By far most known planets are extrasolar!

Most and perhaps all stars host planets!

Transiting Planets: Observables

Experiment:

- choose star
- star properties usually known: M, L, R, T_{eff}
- monitor brightness of a star (very precisely)
- measure *light curve*: flux $F(t)$ over time
- *Kepler*: repeat for thousands of stars

Q: what is planet signature?

Q: measurable properties of this signature?

Q: planet info encoded by these observables?

Transiting Planets: Decoding the Dip

transiting planet signature: **periodic dip in flux**

measurable properties:

- transit (dip) period P
- transit depth: flux drop ΔF
- transit duration: δt

these reveal (some) planet properties:

- $P =$ orbit period
  with star mass + Kepler's 3rd law: *semimajor axis* a
- transit depth $\rightarrow$ planet area $\rightarrow$ planet radius R
- transit duration: time to cross star disk
  if cross equator $\Delta t = 2R_\star / v_{\rm planet}$
  if cross above or below equator $\Delta t < 2R_\star / v_{\rm planet}$
  can use this to infer *orbit inclination*!

Reflex Motion: Star Wobbles Reveal Planets

Getting the most from observable reflex motion

experiment:
track star speed versus time *Q: how?*
search for small periodic variations in speed

Q: what can we directly extract from $v_{\rm obs}(t)$*?*
`www: real examples`

Q what does this tell us about the planet?

Q: what if the planet also transits the star?

Q: what if the planet does not transit the star?

Exoplanet Properties: Decoding the Wobble

1. Wobble Period P

Kepler, Newton: $a^3 = k(m_\star + m_p)P^2$

$\Rightarrow$ planet semi-major axis a

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 $\to$ **planet mass** m_p

Orbit Inclination and Planet Masses

planet orbit plane can be tilted w.r.t. sky
at an angle i: *inclination* of orbit plane
face-on: $i = 0$; edge-on: $i = \pi/2$

measured star wobble speeds are radial, i.e., along line of sight
$\longrightarrow$ measure only one velocity component:

$$v_{\rm obs}(t) = v(t)\ \sin i$$

$\longrightarrow$ velocity gives $M \sin i \leq M$: *lower limit* to planet mass
only the true mass when edge-on $\longrightarrow$ transiting!
`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 $\longrightarrow$ 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 20782 b: e=0.97!`

about $2M_J$, goes from ~ 2.7 AU to 0.04 AU!

$\longrightarrow$ eccentricity range from 0 to 0.97!

suggests dynamical interactions between planets

iClicker Poll: Exoplanet Non-Surprises

Of the following properties of exoplanets discovered by techniques available to date...

which should **not** come as a surprise?

that is, couldn't have been any other way

A most exoplanet masses are large-ish: $M > M_{\mathrm{Earth}}$

B many exoplanets observed with large eccentricities $e > 0.2$

C exoplanet semimajor axes not too large: $a \leq 6$ AU

Exoplanets: Trends and Mysteries

No Surprise: new planets are relatively massive
$\Rightarrow$ needed to get big, observable velocity wobble
or to be large enough to make measurable transit
if not massive/large could not have found!

selection effect=bias: doesn't prove all planets massive
since couldn't find low mass with this technique
$\rightarrow$ largeness of detected mass is statement about detection method,
not about planet properties

similarly: for planet around solar mass star
$a \lesssim 6$ AU corresponds to $P \lesssim 20$ years
selection effect – that's how long we've looked!

Exoplanet Surprises

Big Surprise: very short periods found
$\longrightarrow$ planets are **very** near stars!
ex: τ Boo is 3.6 $\times$ Jupiter mass,
but closer than Mercury's orbit!
nothing like our Jovian planets! "hot Jupiters"

Big Surprise: large eccentricities for giant exoplanets
noncircular orbits exist and are even common!
average giant plant eccentricity $\langle e_{\rm giant} \rangle \approx 0.2$!
larger than all SS giant planets, only Pluto this high
note: small planets have lower eccentricity $\langle e_{\rm small} \rangle \lesssim 0.1$

Exoplanet Trends Continued

Role of heavy elements

- planets more common around stars with high levels of heavy elements ("metals")

$\rightarrow$ clues to formation...

Multiple-Planet Systems

- hundreds of multiple-planet systems seen thus far

Planet Sizes

- in transiting systems can find planet size around that of Jovian planets $\rightarrow$ density $<$ rocky, iron $\rightarrow$ these are gas giants, not terrestrial!
- "super-earths" found: mass $2 - 10 M_\oplus$ *Kepler* sees more of these than Earth-sized!

Exoplanet Trends Continued

Masses

more massive planets easier to find

larger star reflex motions, larger transit eclipses

$\Rightarrow$ first discoveries all Jupiter mass or more

but as techniques have improved,detect smaller masses

now: down to Earth masses and below

Atmospheres

atmospheres detected for some transiting planets!

$\longrightarrow$ only possible for close-in giants in transiting systems

Q: how would this work?

results:

- "hot Jupiters" have gaseous atmospheres
- hydrogen, water vapor, sodium detected!
- evidence for clouds, atmospheric circulation!

Orbit Tilt

for some transiting planets, can measure orbit tilt
with respect to star's spin axis

results:
still very new, but trends seem to be

- orbits found at wide range of inclination angles
  $\rightarrow$ no clear preference for alignment with star spin!
- can be grossly misaligned! particularly acute for giant planets
  appears to sharply contradict solar nebula theory

Binary Stars

most stars are in binaries, and binary stars have planets
found in two configurations that are stable

- circumbinary planets orbit two close binary stars (Tatooine!)
- wide binary stars each have close-in planets

The Habitable Zone

habitable zone defined as:
region around a star
where planets can contain liquid water
Q: is this a reasonable definition? alternatives?

As of today:
290 confirmed or candidate planets in habitable zone
as defined by 180 K $\leq T_{\rm eq} \leq$ 310 K

as seen in HW7 and in Sara Seager talk:
true habitability is complex, depends on:
- planet atmosphere (greenhouse!)
- stellar activity (flares!)
- interactions with star and other planets (tidal locking? seasons?)

Q: lessons?

Other Recent Highlights

red dwarf stars:

low luminosity $L \ll L_\odot \rightarrow$ habitable (?) zone moves inward
shorter periods $\rightarrow$ easier to detect

Trappist-1

coolest red dwarf with known planets

- 7 planets, all earth mass or below
- orbit periods 1.5-19 earth days!
- at least 3 in habitable zone

Proxima Centauri

nearest star to us! red dwarf member of αCentauri triple system
2016: planet found by radial velocity (reflex motion)
mass: depends on unknown orbit inclination i:
$M \sin i = 1.27 \pm 0.18 M_\oplus$ – Earthlike!
$T_{\rm eq} = 230$ K: habitable? but stellar flares frequent and powerful

Exoplanet Statistics

after searching nearby stars, can compare:
stars with planets found via reflex motion
vs total stars searched
ratio gives fraction/percentage of planet-bearing systems

Results

⋆ about $\approx 10\%$ of solar-type stars
have planets of masses (0.3 to 10)M_{Jupiter}
and orbital period $P = 2 - 2000$ days

⋆ extrapolation of observed trends suggests
about $\approx 20\%$ of stars have gas giants at $a \leq 30$ AU

Q: what does this tell us? not tell us? possible biases?

Q: what does all of this mean for solar nebula theory?

Extra-Solar Planets: Implications

Solar Nebula theory: giant planets born far from star
Data: Giant exoplanets found very close
$\Rightarrow$ Theory is incomplete/wrong!

New Planets, New Questions:

1. Who is normal: them or us?
e.g., maybe SS is common, but
others more likely to be found by this technique
Note: current techniques can only now see Jupiter around
nearby star using this method

2. What's up with the very close orbits?

Maybe some giant planets born close in?

Q: why would this be surprising?

Maybe some giant planets be born far, move in?

if so: what stops them from falling into star?

`www: planet eating sketch`

recent **`www: Hubble`** evidence this happens!

3. How to get large eccentricity?

exoplanets show no preference for circular orbits

average exoplanet eccentricity $>$ *all* solar system planets!

Why no large e in SS?

Exoplanets: The Future

NASA *Transiting Exoplanet Search Satellite–TESS*
all-sky survey of bright transiting planets
$\longrightarrow$ will find all transiting planets in all nearby bright stars!

NASA *James Webb Space Telescope – JWST*
will measure atmospheres in potentially habitable planets!

many other space and ground missions
Starshade, microlensing, ...

much excitement,
will play major role in Astrophysics in upcoming decade

Planets are common. Our galaxy teems with alien worlds!
$\Rightarrow$ good news in search for life elsewhere...

Stay tuned!

iClicker Poll: Spring Break Dispersion

Between this moment and next class on March 26

What is the maximum distance you will be from here?

A 0-30 km

B 30-300 km (includes Chicago)

C 300-3000 km (includes NYC)

D 3000 - 10,000 km

E $> 10^4$ km

Enjoy your break!