Finding Exoplanets
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Dragon*Con 2011

Exoplanets

Intro

- “Thus is the excellence of God magnified and the greatness of his kingdom made manifest; He is glorified not in one, but in countless suns; not in a single earth, a single world, but in a thousand thousand, I say in an infinity of worlds.” -- Giordano Bruno, in “On the Infinite Universe and Worlds” (1584), 3rd Dialog.
- # 400 years later, in 1990, Aleksander Wolszczan (voul-schtan) and Dale Frail were working at the Arecibo Observatory in Puerto Rico. They discovered the # pulsar PSR B1257+12. <Description of pulsars> This pulsar was different: it had anomalies in its pulsing period. So Wolszczan and Frail dug deeper. And in 1992, they decided the anomalies could be due to a planet!
    - That’s surprising: pulsars come from # supernovae. Researchers had hypothesized that the explosion would have gotten rid of planets.
    - # But Wolszczan and Frail were cautious. Earlier, in 1991, Matthew Bailes and Andrew Lyne had a paper in Nature saying, “We found a planet around a pulsar!” (PSR B1829-10) Then they came back and said, in Jan 1992, “Whoops, wasn’t true.” They hadn’t taken into account that the Earth’s orbit is elliptical.
    - Wolszczan and Frail looked more closely and decided that, # yes, they’d detected two planets orbiting the pulsar. And when they dug in deeper, they found *three* planets. This is exciting: the first confirmed discovery of an extra-solar planet!
- Exoplanet discovery started to pick up steam. # Next discovery was in 1994, when PSR B1620-26 b was discovered orbiting around a binary star system that had both a pulsar and a white dwarf. Next, # 1995. Didier Queloz and Michel Mayor discovered 51 Pegasi b, which was orbiting around a main-sequence star! In three years we went from finding our first exoplanet to finding our first exoplanet around a sun-like star.
- Since then, # we keep finding more and more and more exoplanets. Why’d it take us so long to find them? Why have we gone from the first officially confirmed ones in 1992 to about 600 today? And how are we seeing them? # [TITLE SLIDE]

The History of Not-Really Exoplanets

- Let’s first talk about why it took us so long to find any. It’s hard to find exoplanets b/c, until recently, you couldn’t directly see them. The planets are like 10 billion times dimmer than their star, the star makes a huge glare that hides the dim planets, and from Earth the stars and planets can be separated by less than a milli-arcsecond.
- That means we have to look for the planets indirectly by seeing what they do to their star, often b/c of the exoplanet’s gravity. We’ve done this before. It’s how we found Neptune!
    - # 1790: Jean Baptiste Joseph Delambre computed # Uranus's orbit. (no...#) Delambre predicted its future position, but it deviated from that prediction
    - # 1841: John Couch Adams says "Uranus’s deviation could be caused by another planet disturbing its orbit" and starts looking for it

- 1845-6: Adams and # a guy named Urbain Le Verrier # independently predict where the new planet should be based on Newton's laws
- 1846: Johann Gottfried Galle finds Neptune right where it should be

- This doesn't always work. # Mercury has a super elliptical orbit. As it goes around the Sun, its perihelion, its point of closest approach, precesses (it moves around). # In 1859, Le Verrier proved that if you have discovered a planet b/c of gravitational problems, then every gravitational problem is an undiscovered planet. He predicts that Mercury's feeling the effects of a planet he called Vulcan # inside Mercury's orbit. Lots of people claimed to see it, but turned out to be wrong.
    - 1916: Einstein explains it! General relativity exactly predicts the precession of Mercury's perihelion. There is no such thing as Vulcan #
- As the story with non-planet Vulcan shows, it's easy to get this kind of thing wrong! So let's talk about the methods we've used to find exoplanets, starting with a couple of stories where, like Le Verrier and Vulcan, people thought they found planets where there were none. Before I begin: one of the thing they say about science popularization is that you should tie it to something in pop culture, like Star Trek or Fringe. So with that in mind, let's talk about non-real exo-planets! #
- The first method is astrometry. It's where you carefully measure where planets and stars and whatnot are over time. If you've got a star and a big enough planet is orbiting around that star, then you'll see the star move in odd ways that you can explain by positing a new planet!
- # First up in our gallery of non-exo-planets, 70 Ophiuchi (off-ih-YOU-key)
    - Binary star. Only about 17 ly away. # Here it is closer in. In 1842 # Johann Heinrich von Mädler saw irregularities in the orbits, setting off a nearly 150-year-long stretch of speculation about planets around 70 Ophiuchi. The biggest claim of an exoplanet came in 1895, from # Thomas Jefferson Jackson See and his sweet, sweet moustache. See measured 70 Off-ih-YOU-key's irregularities and claimed they were caused by a planet. Other people saw irregularities, but didn't claim there was an exoplanet. Nothing could be confirmed, and everyone's irregularities were different! Furthermore, when an astronomer named Forest Ray Moulton published a paper claiming See couldn't be correct b/c the three-body system (star, star, planet) would be unstable, See vituperatively claimed there was no way he could be wrong. # (PS it turns out he was wrong)
    - # In 1943 Dirk Reuyl and Erik Holberg analyzed 10 years of photographic plates of 70 Ophiuchi's motion and said, "Irregularities! There may be a planet around 70 Ophiuchi!"
    - Over the last few decades # W.D. Heintz, at Swarthmore College, re-visited the matter and determined that "unusually large systematic errors in the visual measures of the 19th century" were to blame for See's mistake, and that the irregularities from 1943 haven't shown up.
- # Barnard's Star
    - Red dwarf only 6 ly away. # Peter Van de Kamp, at Swarthmore College, started taking photo plates of Barnard's Star in 1938. He thought he detected a wobble. (On the photo plate, it would be a movement of about 1 um, so he had 10 people measure each plate individually and average the results to find the true center.) After nearly 25 years, in 1963, he said, "I've found the first extrasolar planet!" Big deal!
    - But other astronomers couldn't repeat what Van de Kamp saw. New automated

measuring techniques showed no wobble. And then someone discovered all of the stars on Van de Kamp's plates had the same wobble! There was a systematic error caused when the telescope was disassembled and cleaned and the lenses adjusted. Even # W. D. Heintz, Van de Kamp's hand-picked successor at Swarthmore, said VdK was wrong! But Van de Kamp declared that he was right and everyone else was wrong. # They've yet to find any evidence of a planet around Barnard's Star. #

- (A side-note: both See and Van de Kamp declared that they couldn't be wrong, and fought against those who claimed they hadn't found a planet. Scientists are humans, too, which is why we ask for verification and repeatability of results. Remember PSR B1829-10? No? It's got a catchy name! That's the pulsar about which, in 1991, Matthew Bailes and Andrew Lyne had a paper in Nature saying, "We found a planet around the pulsar PSR B1829-10!" Then they came back and said, in Jan 1992, "Whoops, wasn't true." They hadn't taken into account that the Earth's orbit is elliptical. But when Lyne stood up at the meeting of the American Astronomical Society to announce the mistake, he got a standing ovation for doing the right thing.)
- I tell you all of this to show that finding exoplanets was *hard*. It's gotten easier, but there's still a lot of macho science going on to make it happen.
- Why's it so hard?
  - Stars are bright, and planets are dim. # They're like 10 billion times dimmer than their star, and the star's glare can hide planets.
  - From Earth, stars and their planets appear very close together. They can be separated by less than a milli-arcsecond.
  - The effect of a planet on the star can be hard to detect, unless the planet is super-massive.
  - Earth's orbit and Earth's atmosphere can make detection hard. Remember the not-planet around PSR B1829-10? The effect that Matthew Bailes and Andrew Lyne saw was due to the Earth's orbit being elliptical, and they forgot to account for that.
- What changed? What made it possible for us to find planets?
  - One big thing? # COMPUTERS. Computerizing searches, computerizing models, computerizing everything.
  - Another thing is that practice makes perfect. We've perfected better and better techniques of finding exoplanets.
  - Finally, as we've developed good techniques, we've created specialized missions to look for exoplanets that take one or two techniques and use them for all they're worth.
- So let's talk about those techniques!

Finding Exoplanets

- The big thing we lean on to find exoplanets is # gravity. Planets will drag stars around, making them orbit around the solar system's center of mass. But stars are big and planets are small, so we're talking about a small drag. And how do you see it?
- The first confirmed exoplanet was found because of its effect on a pulsar.
  - # Pulsars *pulse*. They're highly magnetic neutron stars -- the left-over bits from a supernova. They're small and dense, so they rotate really fast. (Angular momentum is conserved, and it's like a spinning skater pulling in their arms going from a star to a neutron star.) Because they're magnetic, the rotating magnet creates a big beam of electromagnetic waves. And this happens fast: the slowest observed pulsar has a period of 8.5 *seconds*. Most of them have millisecond or microsecond periods. Pulsars pulse because the magnetic poles aren't aligned with the rotational axis, so it's like a lighthouse. They give off radio, visible light, x-rays, gamma radiation -- all kinds of EM radiation.

- Pulsars pulse very regularly. That combined with very accurate # clocks here on Earth means we can time light from pulsars down to the nanosecond. You can observe how the pulsar is moving, make predictions about what that will do to when pulses arrive, and then compare your prediction to reality. If reality doesn't agree with your prediction, it could be due to exoplanets dragging the pulsar around! # So that's pulsar timing.
- # That's how Aleksander Voul-schtan and Dale Frail found the first exoplanet around PSR B1257+12. They saw pulse timing differences of +/-1.5 ms. That's less than 1 m/s variation in the star's radial velocity! They also saw microsecond variations due to the planets affecting each other!
- The two planets b and c are about 4x the mass of Earth. But unlikely to have aliens: too much radiation running around the system. #

- But what about non-pulsing stars? How do we find planets around them?
- # Doppler spectroscopy! Stars put out light that has bands missing due to its photosphere absorbing some of that light. # When the planet drags the star towards us, its light is blue-shifted. When it's dragged away, it's red-shifted. That makes those absorption lines move around the spectrum. So if a star's spectral lines shift, then we can guess that there may be a planet there. With new spectrometers, we can see down to a 1 m/s change in velocity. Plus this is distance-independent! This is known as the # radial velocity or Doppler spectroscopy method.
  - # That's how in 1995, Michel Mayor and Didier Queloz discovered 51 Pegasi b, which was orbiting around a main-sequence star! # 1st planet found around a non-pulsar.
  - Doppler spectroscopy has been the most productive method by far. # We've found a butt-ton of stars using this method.
  - Limitations: You need a high signal-to-noise ratio, so only works out to about 160 ly. Ideally the solar system's plane of the ecliptic needs to be mostly pointed to us. You need a big planet that's close to the star. (The Earth causes a radial velocity change in the Sun of about 0.1 m/s, ten times less than what Doppler spectroscopy can see). We can mainly see what're called "hot Jupiters" -- planets that are about as massive as Jupiter and within 0.5 AU of the star. You get a measure of how massive the planet is, but not how big it is.
- # What happens when a planet goes in front of a star? It dims! So we can watch for stars getting dimmer and based on that determine if it has a planet. #
- Fast-forward to # 1999, when we re-confirmed an exoplanet by watching it transit across the star HD 209458, dimming it. That was HD 209458b. First they found it via Doppler spectroscopy. Almost immediately another team saw it transit. 1.7% drop in the star's brightness.
- # 2002: found OGLE-TR-56b by transit alone. Discovered by OGLE, which we'll talk about more in a minute. That's 4,900 ly away!
  - # How much does the star dim? Depends on the size of the star and the size of the planet. But 1-2% isn't uncommon. It's like detecting a fly crawling across a lightbulb from a mile away. #
  - # Limitations: The planet has to pass in front of the star from our vantage point on Earth. Probability of a planetary orbital plane being directly on the line-of-sight to a star is the ratio of the diameter of the star to the diameter of the orbit. About 10% of planets with small orbits have such alignment, and the fraction decreases for planets with larger orbits. For a planet orbiting a sun-sized star at 1 AU, the probability of a random alignment producing a transit is 0.47%. Also, the method suffers from a high rate of false detections. A transit detection requires additional confirmation, typically from the radial-velocity method. You only get the size of the planet, not how big it is. But when you combine this with radial-velocity, you get size + mass. Density!
- Gravitational microlensing. # Say you're watching a star and another star moves between us. You can get microlensing: the gravity of the star in between the Earth and the other star bends light around it, like the lens in glasses. The main thing you see is

that the star appears to get brighter and then dimmer as the object moves in front of and then away from the star, and that happens over the span of days or weeks.

 - That still doesn't let you see planets. But! What if the object that's doing the lensing is a star with a planet around it? That planet can actually make the lensing change. So you measure how the light from the far-away star fluctuates and fit that light fluctuation to theoretical models. #
 - That's what the Optical Gravitational Lensing Experiment # (OGLE -- what a great name) was designed to do. OGLE is from the University of Warsaw. The OGLE team figured out a good method to detect exoplanets via microlensing. And it worked! They found the first planet via gravitational microlensing: # OGLE-2003-BLG-235L b. 19,000 ly away. (Given that OGLE was looking for stars to get brighter and dimmer, you can understand why they also found the first planet detected by the transit method.)
 - Microlensing is good for finding low-mass planets, as it's not as dependent on mass as other methods. But you've only got a little while to see the microlensing event, and then it ain't happening again. The planet is likely to be far away, so it's hard to confirm the planet by other detection means. And you need everything to be in a particularly good alignment -- you can't just pick a star to investigate and say "let's wait for it to have a microlensing event." It's like picking two people in the US and waiting until you and they form a straight line. Instead you watch a bunch of stars all at once and wait for a microlensing event.
- # Why don't we just look for exoplanets directly? Heck, it's how we found Pluto. In 1906 # Percival Lowell and his sweet moustache started looking for PLANET X. He never found it. In 1929 the director of the Lowell Observatory dumped the problem in the lap of # 23-yo Clyde Tombaugh. Clyde spent a year taking photos of the night sky at two-week intervals, then blinking back and forth between them to look for something moving. And # he found Pluto! And there it stayed, until in 2005 # Mike Brown's team at CalTech # killed it.
- Anyway, seeing exoplanets. If only we could deal with that pesky star and its huge glow we could # observe planets directly. One way is to look in the infrared spectrum, where young planets' glows due to their own heat will stand out more. Also, if you're on Earth, it helps to have adaptive optics -- optics that can reshape themselves to deal with distortions caused by our atmosphere.
  - In 2004, an international team used the # Very Large Telescope array in Chile to see # a planet orbiting around a brown dwarf called 2MASS WJ12073346-3932539, or # 2M1207 to its friends. Now, brown dwarfs are more like failed stars, so aren't as bright as regular stars, making it easier to see them, but still! Exciting!
  - The first exoplanet orbiting a main-sequence star that we saw directly was seen in 2008 around # 1RXS J160929.1−210524. Researchers used the Gemini telescope in Hawaii to find it. But it was 330 AU out from the star, so it took a while for researchers to be sure that the planet and 1RXS whatever were moving together, because that's a ways away from the star.
  - This method is limited to young, near-by stars, and works best for planets that are a ways away from the star.
- But what if we could make that light vanish entirely? That's where coronagraphs come in. Coronagraphs let you block just the star's light. Originally # Bernard Lyot invented it to block the sun's light so he could look at its corona, but we can also use this approach

to look for planets around other stars. There's been an exciting new advance in coronagraphs, called the optical vector vortex coronagraph, that takes light at the center of the telescope and making it vanish through polarization trickery. The center light's polarization rotates in such a way that you can get rid of that light, leaving everything else. It also works with small telescopes! # A group at JPL demonstrated this in 2010 by imaging previously-discovered planets around HR 8799.

- # SUMMARIZE METHODS
- I'd be remiss if I didn't mention # Gliese (GLEE-zeh) 581c now.
    - In 2010 there was a lot of excitement about Gliese 581c. It's between about 5 and 10 Earth masses or so, and despite being only 0.1 AU away from its star, was thought to be in the habitable zone around Gliese 581. It's habitable!!! And only 20 ly away! Only, whoops, it's tidally locked, too close to the star, and probably has experienced runaway greenhouse effect. Gilese 581 g, an unconfirmed planet in the system, may be a better one. If it exists, it's only 3 - 4 Earth masses, and it's a whopping 0.15 AU away from the star!

Specialized Exoplanets Missions

- I'd like to end by talking about two missions to space. # COROT. French Space Agency in conjunction with the European Space Agency. Launched at the very end of 2006. It uses the transit method. In 2007 it discovered two new planets. As of June of 2011, it's found 25 confirmed planets.
- # Kepler! NASA launched it in early 2009, and it's in an Earth-trailing heliocentric orbit. It uses the transit method and watches the brightness of some 160,000 stars at once, 100,000 of which are main-sequence stars. # Here's where it's looking. How's it doing? In January 2010, NASA announced that in analyzing the first six weeks of Kepler data, they'd found five new exoplanets. By February of this year they'd discovered some # 1,200 planet candidates. And that only covers data through September 2009! It's found lots of multiple-planet systems, making us believe that multi-planet systems are way more common than we originally thought. Want to help out? All of the Kepler data are being made available at planethunters.org and people are finding new candidates that the Kepler team has not.

Where Do We Go From Here?

- Better techniques. Nulling interferometry to make direct detection better.
- Analyze COROT and Kepler data to find more planets.
- Use all of this data to better understand solar system formation and how the universe works. Why is 1RXS1609 b so far away from its star (330 AU)? A lot of the planets that we've measured via the transit method seem to be larger than we'd expect given their mass? Why so un-dense? Kepler is finding a metric ass-load of exoplanets. Based on that, some astronomers now estimate that 1 out of every 40 to 1 out of every 70 sun-like stars might have planets that are roughly the size of Earth and within their star's habitable zone. Doesn't that make you excited?!?

- Summary of notable exoplanets
    - http://en.wikipedia.org/wiki/List_of_extrasolar_planet_firsts
- List of exoplanets by year
    - http://en.wikipedia.org/wiki/Discoveries_of_extrasolar_planets
- History of exoplanets
    - http://www.nasa.gov/externalflash/PQTimeline/
- http://www.armaghplanet.com/blog/eigh-record-breaking-exoplanets.html

- http://science.howstuffworks.com/planet-hunting3.htm
- Exoplanet catalog: http://exoplanet.eu/catalog.php
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