PHYS#215 - CH#9 - Q & A

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Concept Review

The conservation of angular momentum explains why planetary systems in formation contract into a disk (Section 9.1a). We think that small clumps of dust joined to make **planetesimals**, and planetesimals combined to make **protoplanets** orbiting the **protosun**. In one of the main models for the formation of the Solar System's outer planets (Section 9.1b), a solid core (resembling a terrestrial planet) condensed first for each of the outer planets; the gravity of this core then attracted various types of ice grains from its surroundings, followed by large amounts of hydrogen and helium. Terrestrial planets never became massive enough to accumulate a vast atmosphere because there were few ice particles to accumulate inside the "frost line," and hydrogen and helium gas could not be captured by their weak gravity.

The search for planets around stars other than the Sun, known as **extrasolar planets** or **exoplanets**, has been going on for many decades (Section 9.2). With current technology, they are extremely difficult to see in the glare of their "parent star" (or "host star," the star they orbit), though a few have been directly imaged. Instead, we watch for motions in the star that are caused by something orbiting it, or we look for planetary transits.

The **astrometric method** depends on **astrometry**, the precise measurement of stellar positions and motions; the presence of an unseen planet is deduced from the star's observed wobble in the sky (Section 9.2a). However, so far few exoplanets have been discovered this way. Some planets were finally found in 1991 by timing the radio pulses from a "pulsar," a weird kind of collapsed star to be discussed in Chapter 13, but these are very unusual planets that have little to do with normal planets orbiting Sun-like stars (Section 9.2b).

Most exoplanets discovered with ground-based telescopes since 1995 were found with the **radial-velocity method**, also known as the **Doppler-wobble method** (Section 9.2c), in which periodic changes in the Doppler shift (radial velocity) of a star (the subtle "reflex motion" caused by the orbiting exoplanet) are measured with high-quality spectrographs. But one limitation of this method is that we generally don't know the angle of the plane in which the planets are orbiting their parent stars; thus, only the *minimum* mass of each planet can be derived. This problem left the nagging question of whether the objects were really planets or merely low-mass companion stars.

The discovery of a three-planet system helped dispel these concerns, as did the large observed gap in mass between the purported exoplanets and the lowest-mass stars. Now many such planetary systems are known. Moreover, we have found many "super-Earths" in which the planet appears to be rocky (rather than a gas giant) and has a mass less than 10 Earth masses (down to just a few Earth masses). At present, even Earth-mass planets and smaller are being found with this method.

Another very successful technique for finding exoplanet candidates (called the **transit method** or **blink method**) is by looking for the very slight drop in a star's light as an exoplanet **transits** across the face of its parent star (Section 9.2d). These candidates must then be verified with the Doppler-wobble technique, and most of them end up being genuine exoplanets. For these systems, we know that the inclination of the orbital plane is close to 90 degrees, so the mass of the exoplanet can be accurately determined. With the Kepler mission, including its K2 phase, plus some observations from ground-based telescopes, thousands of exoplanet candidates and over 1000 confirmed exoplanets have now been observed. In a few cases, the transit method has revealed – through spectroscopy – hydrogen, sodium, and other gases in the exoplanet's atmosphere.

With sophisticated equipment, we are now beginning to obtain direct images of exoplanets, especially young systems viewed at infrared wavelengths (Section 9.2e). When the images of a given system are separated by a few years, the orbital motion of exoplanets can even be detected. Another method for finding exoplanets involves **gravitational microlensing** (Section 9.2f), though it is extremely difficult to conduct additional follow-up studies of the microlensing exoplanets. Exoplanets constitute one of the most exciting and fast-paced areas of modern astrophysics, and many additional projects will soon be conducted or are in the planning stages (Section 9.2g).

The first exoplanets discovered were giant planets, though less massive, terrestrial planets (with rocky surfaces) are being increasingly found in those planetary systems. Exoplanets are often in quite eccentric (elongated) orbits, perhaps as a result of previous gravitational encounters with other planets or the protoplanetary disk (Section 9.3). Some of the planets are in circular orbits very close to their parent stars, which probably means (according to the Nice model) that they were formed elsewhere in the systems and later drifted inward.

Astronomers are now intensively looking for **Goldilocks planets** – that is, exoplanets in the habitable zone, in which water can exist in the liquid state, being neither too hot nor too cold (Section 9.4). Exoplanets in or near the habitable zone have already been found, and a few are even small enough to have rocky surfaces.

Some of the objects found with the Doppler-wobble technique might actually be **brown dwarfs**, which are sometimes called “failed stars” because they don’t fuse ordinary hydrogen into helium (Section 9.5). They can be thought of as links between planets and normal stars. Planetary companions to some brown dwarfs have been imaged at infrared wavelengths.

We are increasingly finding signs that planetary systems are forming around other stars (Section 9.6). A probable disk around the star β (beta) Pictoris, and apparent protoplanetary disks around additional stars observed with the Hubble Space Telescope and other telescopes seem to be direct observations of planetary systems in formation.

Questions

1. What is the difference between a protoplanet and a planet?

2. What role do planetesimals play in the origin of the planets?

3. Discuss similarities and differences in the way terrestrial planets and giant planets formed in our Solar System.

4. How does the pulsar–planet system (Section 9.2b) differ from the exoplanet systems discovered subsequently?

5. Why is it difficult to obtain direct images of exoplanets?

6. Explain the methods by which most planets were discovered around other stars, both in the early stages and more recently.

7. Does the Doppler-wobble method for deducing the existence of a planet orbiting a star depend on the star's distance from Earth? (Assume the star's apparent brightness is independent of distance.)

†8. It turns out that the ratio of the speed of a planet to the speed of its parent star (as they orbit their common center of mass) is equal to the inverse of the ratios of their masses. If Earth orbits the Sun with a speed of 30 km/s, what is the Sun's corresponding orbital speed (i.e., its "reflex motion," induced by the Earth's motion)?

9. Why may it be that at first only giant planets and not terrestrial planets were discovered around other stars?

10. Why can we measure only the minimum of the mass of an exoplanet using the Doppler-wobble method alone?

11. Many of the giant exoplanets are quite close to their parent stars. If they initially formed farther out, how could they have ended up at their observed positions?

12. What was the special importance of the discovery of a system of several (rather than just one) planets orbiting a star?

13. What are two reasons that the discovery of a planet transiting a Sun-like star is desirable?

†14. If a transiting planet has 10 per cent the diameter of its parent star, the observed brightness of the star will dim by what percentage during the transit?

15. Give two reasons why the discoveries of "super-Earth" exoplanets instead of much more massive planets are important.

16. Discuss some of the main discoveries of the Kepler satellite.

17. Why is it easier to discover transiting exoplanets, especially small ones, with a telescope in space than with ground-based telescopes?

18. How can studies of transiting exoplanets be used to determine at least some of the types of molecules present in their atmospheres?

19. Describe what is meant by the term "Goldilocks planet."

20. Why are the orbital periods of Goldilocks planets around stars less powerful than the Sun generally shorter than 1 Earth year?

21. How do brown dwarfs differ from planets and from stars?

22. Why is β (beta) Pictoris an interesting object?

†23. If the temperature of a dust ring around a star is 30 K, at what wavelength does its blackbody spectrum peak? In what spectral region is this wavelength?

24. Discuss how the Kuiper belt in our Solar System may be related to some of the observed phenomena found around other stars.

25. Why do infrared observations help us learn about planetary systems in formation?

26. Describe the basic idea of gravitational lensing and its application to exoplanets.

27. True **or false?** Many of the known exoplanets are peculiar compared with planets in our own Solar System; these exoplanets have very eccentric orbits, or they orbit very close to the star.

28. True or false? Exoplanets can be detected by monitoring the brightness of a star, and seeing it decrease as the planet blocks part of the star's light.

29. True or false? When viewing an exoplanet orbit edge-on (i.e., your line of sight is along the orbital plane), the star's measured radial velocity can be used to determine the star's actual orbital speed.

30. True or false? The small number of low-mass, Earth-like exoplanets found around normal stars in the first decade of exoplanet research was surprising; with the then-available technology, they should have dominated our discoveries, if they are indeed plentiful.

31. True or false? Many exoplanets have already been found with the astrometric method, in which a star's measured position in the sky moves back and forth very slightly.

32. True or false? The periodic Doppler-shift method is biased toward finding planets whose orbital plane is along the line of sight, rather than those close to the plane of the sky.

†33. True or false? A transiting exoplanet that blocks 0.01 per cent of the parent star's light has of the star's radius.

†34. True or false? If 20 per cent of stars have Earth-like planets in the habitable zone orbiting them, and there are about 1 trillion stars in our Local Group of galaxies (of which the Milky Way Galaxy is a member), then there are roughly 200 billion such planets in the Local Group of galaxies.

35. True or false? Exoplanets orbiting other stars should obey Kepler's three laws of motion, more specifically Newton's versions of them, but in each case their host star replaces the Sun.

36. Multiple choice: Using ground-based telescopes, a large number of massive exoplanets orbiting other stars have been found by **(a)** looking at a massive planet's Doppler-shifted light as it orbits the star; **(b)** taking spectra of the star to look for contamination from the light of a massive planet; **(c)** looking for a periodic Doppler shift in the star's spectrum as a massive planet causes the star to wobble slightly; **(d)** pointing the telescope to a spot about 5–10 au away from the star, knowing that massive planets can only orbit near that distance; or **(e)** measuring the Doppler shift of the star, and seeing whether it keeps on increasing with time, as would be expected if a massive planet were pulling on it.

37. Multiple choice: The giant (jovian) planets are large compared with the terrestrial planets because the giant planets **(a)** have higher densities; **(b)** formed by the same process as the Sun, and can be considered miniature stars; **(c)** have many moons; **(d)** obtained and retained more gas and ice due to their large distance from the Sun; or **(e)** did not suffer as many major, destructive collisions as the terrestrial planets (like Earth, when the Moon formed).

38. Multiple choice: Suppose you are searching for exoplanets using the radial velocity and transit techniques.

Which exoplanets are you *most* likely to find? (a) Jovian exoplanets orbiting with a large semimajor axis. **(b)** Jovian exoplanets orbiting with a small semimajor axis. **(c)** Terrestrial exoplanets orbiting with a large semimajor axis. **(d)** Terrestrial exoplanets orbiting with a small semimajor axis**. (e)** There is an equal chance of finding both jovian and terrestrial exoplanets, and an equal chance of finding ones with large and small semimajor axes.

†39. Multiple choice: Suppose exoplanets Noelle and Alex both orbit the same star. The orbital period of exoplanet Noelle is 8 times that of exoplanet Alex. Compared with exoplanet Alex, exoplanet Noelle is ______ from its star. **(a)** ¼ as far; **(b)** ½ as far; **(c)** 2 times as far; (d) 4 times as far; or **(e)** 8 times as far.

40. Multiple choice: Jupiter's chemical composition is most similar to that of **(a)** Earth; (b) the Sun; **(c)** Pluto; **(d)** Venus; or **(e)** meteorites.

41. Multiple choice: Imagine a star with a single exoplanet orbiting it. If the exoplanet's mass were doubled, the observed Doppler-shift variations of the star would be _______. If the semimajor axis of the exoplanet's orbit were doubled, the observed Doppler-shift variations of the star would have _______. **(a)** larger; a shorter period; **(b)** smaller; a longer period; (c) larger; a longer period; **(d)** the same; the same period; or **(e)** smaller; a shorter period.

42. Multiple choice: Since 1995, about 1000 exoplanets around normal main-sequence stars have been detected with ground-based optical telescopes using the Doppler-wobble method. Which one of the following statements about these planets is *true*? **(a)** All of them are less massive than Jupiter. **(b)** In many cases, the planet's mass is as small as Mercury's mass. **(c)** The measured masses of the planets are generally only upper limits; that is, their true masses might be smaller, but not larger. **(d)** In some cases, they are so close to their parent stars that they complete a full orbit in only a few days. **(e)** They all have circular or nearly circular orbits.

43. Multiple choice: At the present time, most of the known exoplanets or exoplanet candidates have been found by using **(a)** astrometric measurements; **(b)** the Doppler-wobble method; **(c)** direct imaging; **(d)** gravitational microlensing; or **(e)** the transit method.

44. Multiple choice: Suppose you are measuring the brightness change of a star over time due to an exoplanet orbiting the star. What are the properties of this exoplanet that you can deduce *directly* from the star's light curve (plot of brightness vs. time)? **(a)** The exoplanet's orbital period, and the ratio of its radius to the host star's radius. **(b)** The exoplanet's orbital period and its distance from the host star. **(c)** The exoplanet's distance from its host star, and the ratio of its mass to the host star's mass. **(d)** The exoplanet's distance from its host star and the exoplanet's density. **(e)** The composition of the exoplanet's atmosphere.

45. Fill in the blank: Objects having low masses compared with normal stars, but higher masses than planets, are known as ________, and are sometimes called "failed stars."

Brown dwarfs

46. Fill in the blank: Theories of the formation of the Solar System suggest that planets formed through the accumulation of ________, much smaller bodies.

Planetesimals

47. Fill in the blank: A planet and its parent star orbit their common __________, though it is far closer to the star than to the planet.

Center of mass

48. Fill in the blank: In 2004 and 2012, astronomers measured a slight dimming of the Sun when _______ transited across it.

Venus

49. Fill in the blank: A spinning, collapsing cloud of gas and dust forms a disk because of the conservation of

Angular Momentum

Kepler

50. Fill in the blank: The ____________ satellite has found a huge number of transiting exoplanet candidates. †This question requires a numerical solution.