Cume #453
70 Points Possible, 50 Points is a Guaranteed Pass
Administered September 11, 2021

The Second Discovery from the COol Companions ON Ultrawide orbiTS (COCONUTS) Program: A Cold Wide-Orbit Exoplanet around a young Field M Dwarf at 10.9 pc

Zhoujian Zhang, Michael C. Liu, Zachary R. Claytor, Willam M.J, Best, Trent J. Dupuy, and Robert J. Siverd.
ApJL 2021 (https://arxiv.org/abs/2107.02805), 11 pages

You may use a calculator, but no programmed formulae. Clearly start each question (by number) in the exact order the questions appear.

Some values you may find useful:
G = 6.67e-8 erg/s/cm^2/g^2
1AU = 1.50e13 cm
Solar mass: 1.99e33 g
Jupiter mass: 1.90e30 g
Astronomer definition of giant planet: <13 M_{Jup}
Astronomer definition of brown dwarf: 13-80 M_{Jup}

If you get stuck on the first part of a calculation but do know how to complete the downstream parts, then you are encouraged to assume an answer for the first part, state your assumption, and proceed.

1) [13 pts total] Let's start by reviewing the main points from the paper.

1a) [5 pts] Explain the main discovery of this paper, in about 3-4 sentences. Or, put another way, what is the COCONUTS-2 system?

1b) [5 pts] Explain what measurements and analysis were used to make this discovery (4-5 sentences).

1c) [3 pts] Typical searches for extrasolar planets study a star and attempt to detect a planet. Why was the discovery of COCONUTS-2b different from this usual pattern? (1-2 sentences)

2) [10 pts total] Good figures are one of the most important parts of an astronomy paper. Let's take a deeper look at some of the figures.

2a) [4 pts] Consider Figure 1, particularly the three panels to the right and the bottom. What conclusions are we meant to draw about the COCONUTS-2 system from these three panels, and the locations of the red, blue, and gray points?

2b) [6 pts] All four panels of Figure 1 are 2D slices of a 6-dimensional phase space. However, one of the 6 dimensions is missing.
(i) What are the five plotted dimensions,
(ii) and what is the missing sixth dimension?
(iii) Why do you think this missing dimension does not appear in this figure, or elsewhere in this paper?

3) [13 pts total] Section 5 of the paper calculates the expected orbital period of the system.

3a) [3 pts] The authors don't explicitly give the equation they used to calculate this period. Given their explanation:
(i) write down the equation they must have used
(ii) and give its name.

3b) [6 pts] Assume the orbit is face-on and circular (e=0), and has the semi-major axis given in the paper: 7506 AU.
(i) What is the circumference of this orbit on the sky, in arcseconds?
(ii) Given the orbital period stated in the paper, 1.1 Myr, how much orbital motion do we expect over 1 year, in AU?
(iii) How much is this in arcseconds on the sky per year?

3c) [4 pts] As astronomers living on Earth, the paper authors note the parallax for the star COCONUTS-2A to be 91.826 mas. (Technically this measurement comes from the *Gaia* satellite, which is in orbit around the Earth, but that's close enough to "being on Earth" for our purposes). If an astronomer lived on COCONUTS-2b and observed our Sun, what parallax angle would they measure for the Sun as they orbit their star? (express your answer in both arcseconds and degrees, and assume we can still use the small angle approximation)

4) [9 pts total] Let's look at the overall properties of the host star, COCONUTS-2A.

4a) [3 pts] The authors give a median age for the system of 500 Myr. For purposes of this question and the next one, let's round off the actual age of the Milky Way galaxy to 10 Gyr. Assuming the star formation rate of the Milky Way disk has been constant for these past 10 Gyr, what "age percentile" does COCONUTS-2A fall into, compared to all other stars that currently exist (or have existed in the past) **that are the same mass as COCONUTS-2A**? That is, are 50% of similar-mass stars younger, and 50% older? 20% younger, 80% older? Some other set of percentages?

4b) [6 pts] For the other stars in the galaxy with the same mass as COCONUTS-2A that exist now or have ever existed,
(i) about what fraction should be pre-main sequence (hint: reread the last two paragraphs of section 3.2 in the paper),

(ii) what fraction should be on the main sequence,
(iii) and what fraction should have evolved off the main sequence?
(iv) How do you know?

5) [14 pts total] Section 4 of the paper considers both "hot-start" and "cold-start" models, but never really defines the terms. Let's see if we can work out what these mean from context.

5a) [4 pts] From Figure 4, consider the "hot-start" and "cold-start" Sonora-Bobcat models (purple and teal solid lines, respectively). Describe qualitatively how the behavior of these two model sets differ in this figure as a function of age.

5b) [6 pts] Given your answer to 5a, the Stefan-Boltzmann law, and this one extra piece of knowledge (Planets and brown dwarfs, from about 1 Jupiter mass up to 80 Jupiter masses, regardless of age and mass, all have about the same radius: 1 Jupiter radius): can you justify why these two sets of models are called "hot-start" and "cold-start"?

5c) [4pts] Consider the planet 51 Eri b in Figure 4, and assume the error bars on the figure are correct. If we knew (somehow) that 51 Eri b formed via cold start, but wanted to know which cold start model (Sonora-Bobcat or Spiegel & Burrows) was correct,
(i) which property/quantity of 51 Eri b would we want to measure?
(ii) Describe one way we might make that measurement (Hint: 51 Eri b is an exoplanet that orbits its star at 13 AU).

6) [11 pts total] Finally, let's think a little about what makes this system so interesting.

6a) [3 pts] Near the end of the paper, the authors calculate the binding energy of the system, and make a note about how it compares to other imaged exoplanets orbiting stars. For comparison, what's the binding energy of Jupiter and our Sun, when Jupiter is at perihelion? (Hint: Jupiter has a perihelion distance of 5 AU)

6b) [4 pts] The paper gives the binding energy of the COCONUTS-2 system with relatively large error bars (about 60%), so those error bars must come from uncertainty in the individual terms in the binding energy equation.
(i) Which two terms in the binding energy equation do you think are most uncertain, and
(ii) why are these two terms so uncertain?

6c) [4 pts]
(i) Why is the binding energy significant? (Or put another way, why did the authors go through the trouble to quote this number in their final three paragraphs?)
(ii) Given your answer to 6b (i), why is the age of this system (and in particular your answer to 4a) significant when thinking about how common systems like this should be?