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?

This paper describes the discovery of a 6-Jupiter mass exoplanet (COCONUTS-2b) orbiting COCONUTS-2A, a young, nearby M star. The separation between the planet and star is surprisingly large, 600" on the sky (or about 1/6th of a degree) in angular separation, and over 6000 AU in physical separation. This system is also relatively young, with an age range quoted between 150 and 800 Myr, and nearby: only 11 pc from us. The paper notes that of all exoplanets directly imaged so far, COCONUTS-2b is the second coolest, second widest, and closest to Earth.

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

The planet, COCONUTS-2b, had been previously identified as a free-floating brown dwarf (or planet), and has a measured parallax and proper motion from ground-based analysis. The *authors used Gaia EDR3 data to search for a star that is physically close to COCONUTS-2b and is moving in the same direction through space, identifying the M3 star COCONUTS-2A. They then calculated a low probability of chance alignment, and found the age of the system using literature measurements of the star: lack of lithium absorption, strong H-alpha, X-ray, and UV emission, a relatively fast 2-day rotation period, and comparison to the the main sequence on the HR diagram all point to the star having an age between 150 Myr and 800 Myr. Using this age of the system, and luminosity of COCONUTS-2b derived from its photometry and distance, they use theoretical evolutionary models to find a mass of the planet of 6 MJup (using the "hot start" models). Near-infrared photometry of COCONUTS-2b across multiple bands and comparison to atmosphere models suggest a cool 400K temperature for the planet.*

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)

Unlike the typical pattern, in this case the planet was discovered first (in 2011), identified as a free-floating object, and the host star was identified in this paper to be physically bound to the planet almost a decade later. It was only by finding it to be associated with a young star that it could be demonstrated that COCONUTS-2b was a planet, and not a brown dwarf.

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?

These figures demonstrate that the two objects, COCONUTS-2A and COCONUTS-2b are physically associated, and consistent with a host star being orbited by a very wide planet. While most stars in that direction of the sky from Gaia EDR3 have small proper motion and parallax, these two objects are significantly closer and moving faster, but have very similar proper motions and parallax, indicating that they are physically associated, and that a chance alignment is very unlikely.

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?

The six dimensions are 3 dimensions of position and 3 dimensions of velocity. Shown in the figure are RA and Dec position, and proper motion (velocity) in RA and Dec, as well as parallax (position in the line of sight direction). The missing dimension is velocity along the line of sight, or radial velocity. Radial velocity is given for the star COCONUTS-2A in Table 1, but not for the *planet: spectra are required to measure a radial velocity, and the paper never mentions spectra of the planet, either from this work or in past literature analysis. Given how faint the planet is (H=20), a high resolution spectrum would require significant observing time on a large telescope.*

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.

The text notes how they calculate semi-major axis, and that they combine it with the primary star's mass to derive an orbital period. Given this explanation, they used Kepler's third law, which gives P^2 = a^3 / M

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?

The median value for semi-major axis stated in the paper is 7506 AU, so a circle with this radius will have a circumference of
*C = 2pi R = 2 * 3.14 * 7506 AU = 47200 AU, then converting to arcseconds: 47200/10.9 = 4330"*
If we assume the orbit is face-on and circular, it will orbit with a constant velocity, completing one orbit every 1.1 Myr. So the planet will move 0.043 AU per year. To convert this to arcseconds, we note the paper gives the distance to the star to be 10.9 pc, so multiplying we find that the planet moves 3.9 mas/year due to orbital motion (similar to the size of the current error bar on the proper motion measurement of the planet).

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)

The parallax for the star is given to be 91.826, as measured by Gaia. Parallax (from Earth) represents a right triangle with parallax angle opposite to a side with length 1AU, and adjacent side equal to the distance, and in the small angle approximation:

*theta ~ 1 AU / (206265 * d_in_pc). For our alien colleague, their parallax triangle will have an opposite side equal to 7506 AU, instead of 1 AU. The distance from the Earth/Sun to COCONUTS 2A/b is the same in both cases, so the parallax angle must get larger by a factor of 7506: parallax angle = 7506 * 91.826 mas * (1" / 1000 mas) = 690 arcseconds, or about 0.2 degrees.*

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?

Using our central value for the age of COCONUTS-2 of 500 Myr, we expect 500/10000 stars to be younger, and 9500/10000 stars to be older, given a constant star formation rate. That is, we expect 5% of similar-mass stars to be younger than COCONUTS-2A, and 95% to be older.

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?

Table 1 gives the mass of COCONUTS-2A as being 0.37 solar masses, considerably less than our Sun, which has a main sequence lifetime of 10 Gyr. Given that, 0% of these stars should have evolved off the main sequence, since the galaxy is not old enough for even the oldest of these stars to have yet evolved off the main sequence. The paper states that the pre-main sequence lifetime for stars with the same mass as COCONUTS-2A is about 100 Myr, and so with an age for the galaxy of 10 Gyr, about 1% should be pre-main sequence, and 99% should be on the main sequence.

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.

The hot-start iso-mass contours are (mostly) straight lines, and as we move to smaller and smaller ages these models imply higher and higher luminosities. The cold-start models, on the other hand, especially for 6 and 10 MJup, turn over at younger ages, predicting a much lower luminosity at young ages. So "hot start" models are very luminous at young ages, while "cold start" models are less luminous. At older ages, the two sets of model tracks start to overlap more

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"?

The Stefan-Boltzmann law tells us that the luminosity of an object is given by:
*L = sigma * T^4 * A, where T is temperature and A is surface area. If all planets and brown dwarfs have the same radius, they all have the same surface area. As a result, we can conclude that more luminous objects must be hotter. Thus, the "hot start" models, which we saw in the plot were more luminous at younger ages, must also be hotter at young ages. The "cold start" models were less luminous at younger ages, so they must be comparatively cooler. Put another way, "hot start" is a model that starts hot, hotter than the "cold start" models, which start cooler.*

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).

Given the errors on the 51 Eri b point, it crosses the Sonora-Bobcat cold start models on the 2 M_{Jup} iso-mass contour. It crosses the Spiegel & Burrows cold start models on the 10 M_{Jup} iso-mass contour. Thus, the two models make different predictions for the mass of this planet, and if we could measure the mass directly we could tell which set of models was correct (assuming we knew it was a cold start planet). Since 51 Eri b is an exoplanet orbiting a star, we could measure its mass using the reflex motion of the star it orbits, either using radial velocity measurements of the star over time, or absolute astrometry of the star over time (for example, from the Gaia mission).

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)

Binding energy is the difference between the potential and kinetic energy. Gravitational potential energy is given by: $PE = -GMm / R$, *and kinetic energy is* $KE = (1/2)mv^2$. *For a circular orbit,* $a = v^2/R$, *and* $GM/R^2 = a = v^2/R$, *which gives* $v^2 = GM/R$, *and so* $KE = (1/2) GMm/R$. *So finally,* $BE = PE + KE = -GMm/(2R) = -(6.67e{-8}) * (1.99e33) * (1.90e30) / (2 * 5 * 1.50e13) = -1.68e42$ *ergs, about a thousand times greater amplitude than the binding energy of COCONUTS-2.*

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?

Other than the constant G (that we assume is pretty well-known), there are only three terms in the binding energy equation: mass of star, mass of planet, and separation between the two. The mass of the star seems to be pretty well-known, given as 0.37 +/- 0.02 M_sun in the paper. So by process of elimination, the most uncertain terms must be the mass of the planet and separation. The paper calculates the mass of the planet from theoretical models, and different models given different masses: the quoted masses in their 1-sigma ranges vary from 4 Jupiter masses up to 12 Jupiter masses. The separation is also not well known since we can (currently) only observe the projected separation, which is separation in 2 of the 3 dimensions. The line-of-sight distance has relatively large error bars, given the large errors on parallax of the planet, compared to the well-known parallax of the primary star.

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?

The COCONUTS-2 system is much more weakly bound than Jupiter is to our Sun, implying the system is more "fragile." A smaller kick, such as the gravitational attraction from another star that passes close to the system, would be required to eject the planet from the system.
In 4a we found the age of the system is low compared to other stars of this mass, this star is younger than 95% of other similar stars. As these stars move through the galaxy, they will have close encounters with other stars, and an older system will have more close encounters, and so more opportunities for the gravity of that passing star to unbind the system. So the fact that this is a younger system may explain why it hasn't been stripped apart yet, it hasn't had as many dangerous close encounters.