How Two Old and Unrelated Exoplanet Systems Turned Out to Be 350-million-year-old Siblings

Age-dating stars based on how fast they spin shows that Kepler 52 and Kepler 968, two exoplanet host stars, are members of a large, sparse cluster called Theia 520.

by Jason Curtis, Marcel Agüeros, et al.

A team of astronomers from New York and California has discovered that two stars, each home to three small exoplanets, are members of a newly identified cluster of nearly 400 stars. Previously, the stars were thought to be isolated and quite old, with ages estimated to be between 3 and 16 billion years. But by combining data from the European Space Agency's Gaia telescope, NASA's Kepler and TESS space telescopes, and from the Zwicky Transient Facility, located in southern California, the team, led by Jason Curtis of Columbia University, confirmed that Kepler 52 and Kepler 968 belong to a cluster of stars all born only 350 million years ago. Now that precise ages can be assigned to these exoplanets, they can be used to understand the evolutionary processes that impact planets in the first billion years of their lives, a period that we still know relatively little about. Dr. Curtis will present these results, which demonstrate the power of combining very different observations of stars, at the upcoming 238$^{\text{th}}$ meeting of the American Astronomical Society in June 2021, and the team is preparing a manuscript for publication in the AAS Journals.

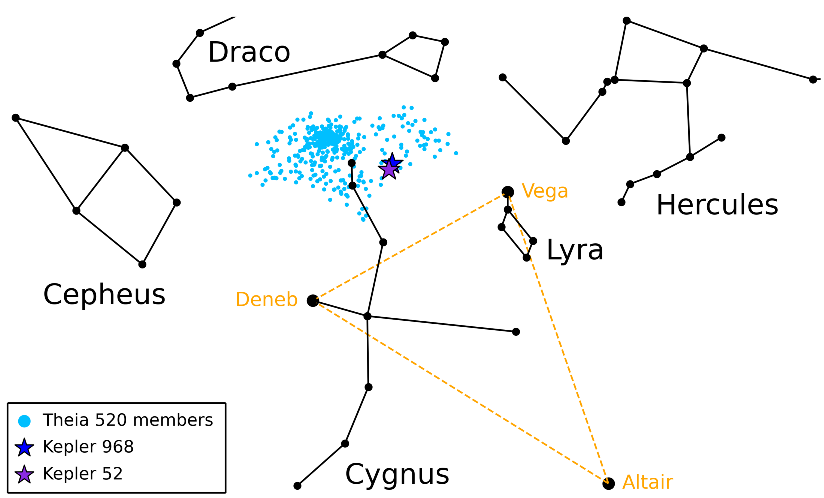

Figure 1: Theia 520 is located 1200 light-years away and appears between the constellations of Cygnus and Draco, near the Summer Triangle (shown in orange). Its stars are shown as blue dots, and Kepler 52 and Kepler 968 are marked with purple and dark-blue five-point stars, respectively. Observations from Gaia, Kepler, TESS, and ZTF show that Theia 520 is about 350 million years old. Credit: Jason Curtis.

As their names imply, Kepler 52 and Kepler 968 were discovered by NASA's Kepler mission. Kepler monitored the brightness of tens of thousands of stars, recording measurements every 30 minutes for nearly four years straight. These observations were designed to detect the temporary and periodic dimming caused by any planets that might be orbiting these stars when these planets passed in front of them. Kepler was incredibly successful, identifying thousands of exoplanets, including Kepler 52 and Kepler 968. The amount of star light each planet blocks ($\sim 0.1\%$) reveals that they are all approximately twice the size of Earth. However, that is where the similarity ends. These planets orbit much more closely to their stars; the closest completes its orbit in just under

4 days and the furthest takes 36 days which is still only 40% of the duration of Mercury's orbit around our Sun.

Kepler 52 and Kepler 968 are both K dwarfs, stars with masses roughly 60% that of the Sun. This means that they have lifespans much longer than the Sun's, and that their observable properties, such as their temperatures and luminosities, will change very little over billions of years. As a result, determining the ages of these stars using astronomers' usual techniques, which rely on comparing those observable properties to predictions from stellar evolution models, is not practical. A recent survey attempting to infer ages for all Kepler stars with luminosities measured from Gaia data could not determine a reliable age for these stars due to their slowly evolving temperatures and luminosities—the resulting values of 3-16 billion years for Kepler 52 and Kepler 968 span nearly the full history of the Universe.

Fortunately, stars like the Sun reveal their ages in another way. Stars are born rotating rapidly, spinning on themselves anywhere between once every few few hours to once every few days. Over time, this rotation slows; today, the Sun now takes 26 days to complete one rotation. Critically, the more rapidly rotating stars brake more efficiently, causing stars of the same mass and age to eventually spin at the same rate. The result is that plotting rotation rates as a function of the masses of stars of the same age traces out tight sequences, the precise pattern of which depends on the age of the group.

Unfortunately, it takes a few hundred million years for these tight sequences to form, so even this technique cannot be applied to precisely age-date young stars in isolation. Therefore, the best way to precisely age-date stars and their planets is by associating them with their birth cluster.

In 2019, Marina Kounkel and Kevin Covey of Western Washington University used data from the Gaia mission to identify thousands of new stellar groups within a few thousand light years of the Sun, completely transforming our view of our stellar neighborhood. In an effort to identify those most worthy of characterizing in more detail, Dr. Curtis and his team sifted through data for the nearest two hundred groups. Theia 520 immediately drew Dr. Curtis's attention. Its Hertzsprung–Russell Diagram, which shows the distribution of surface temperatures and luminosities for the stars in the cluster, indicated that it was 300-400 million years old. This would make it a promising target for stellar astrophysics, as few nearby clusters are known at this age.

Dr. Curtis's interest in Theia 520 was further piqued when he realized that the southern portion of Theia 520 had been serendipitously observed by Kepler, and that part of its northern portion falls in the part of the northern sky surveyed by NASA's Transiting Exoplanet Survey Satellite (TESS). "I was shocked when I noticed that stars in Theia 520 had been observed by both Kepler and TESS," said Dr. Curtis. "I got even more excited when I realized we could also add data from the Zwicky Transient Factory to measure rotation periods for Theia 520 stars that were missed by the space missions."

Using tools that he developed with a team of three high-school students at the American Museum of Natural History, Dr. Curtis proceeded to determine the rotation rates of 130 stars in Theia 520. As he had hoped, the stars in the new cluster formed a tight sequence. By comparing its position to that of other well-studied star clusters, he concluded that Theia 520 is 350$\pm$50 million years old.

When Dr. Curtis then matched his catalog for the cluster to that of known planet-hosts, he was pleased to find that among Theia 520's members are Kepler 52 and Kepler 968. "Planets in clusters provide us with a snapshot in time," said Dr. Elisabeth Newton, an astronomer at Dartmouth College who was not involved in the study. "When we know exactly how old planets are, we can use them to piece together the story of how planets and planetary systems evolve. Knowing that Kepler 52 and 968 are only a few hundred million years old is especially valuable because we haven't yet found many planets that young."

Remarkably, the data used in this work were all publicly available online. "This exciting result underscores the importance of all-sky surveys and of supporting public archives for maximizing the

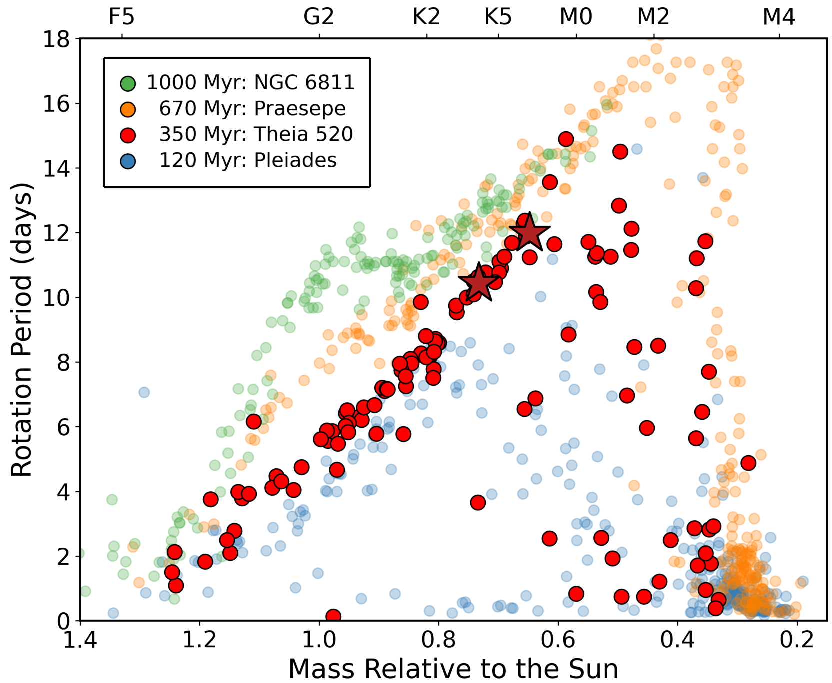

Figure 2: The distribution of rotation periods as a function of mass and spectral type for members of Theia 520 and for other, well-known stellar clusters. The stars in Theia 520 form a tight sequence for stars between 0.6 and 1.2 times the mass of the Sun. The position of this sequence relative to those seen in the Pleiades (120 million years old) and Praesepe (700 million years old), two benchmark open clusters, indicate that Theia 520 is roughly 350 million years old. Keplers 52 and 968 are marked as dark-red five-point stars. Their rotation periods are consistent with Theia 520's slowly rotating sequence, thus corroborating their membership and youth. Credit: Jason Curtis.

scientific impact of observational facilities," said Dr. Marcel Agüeros, an astronomer at Columbia University and a co-author of the study.

"This is only the beginning," said Dr. Curtis. "Gaia has shown that the solar neighborhood is teeming with coeval populations, some stretching hundreds of lightyears in space in elongated patterns, others arranged in more amorphous distributions, and some that are dense clusters with halos and tails. Like Theia 520, some of these groupings are home to already known planets, with many more waiting to be discovered with the ongoing TESS survey."

Dr. Curtis is an associate research scientist at Columbia University's Department of Astronomy. He conducted this work with astrophysicists Marcel Agüeros of Columbia University, Luke Bouma of Princeton University, Sam Grunblatt and Trevor David of the American Museum of Natural History, Andrew Howard of Caltech, Howard Isaacson of UC Berkeley, Kevin Covey and Marina Kounkel of Western Washington University, and Angeli Villegas, Isabella Fraczek, and Linus Brooks who contributed while in high school through the Science Research Mentoring Program at the American Museum of Natural History.

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