Baby Solar System

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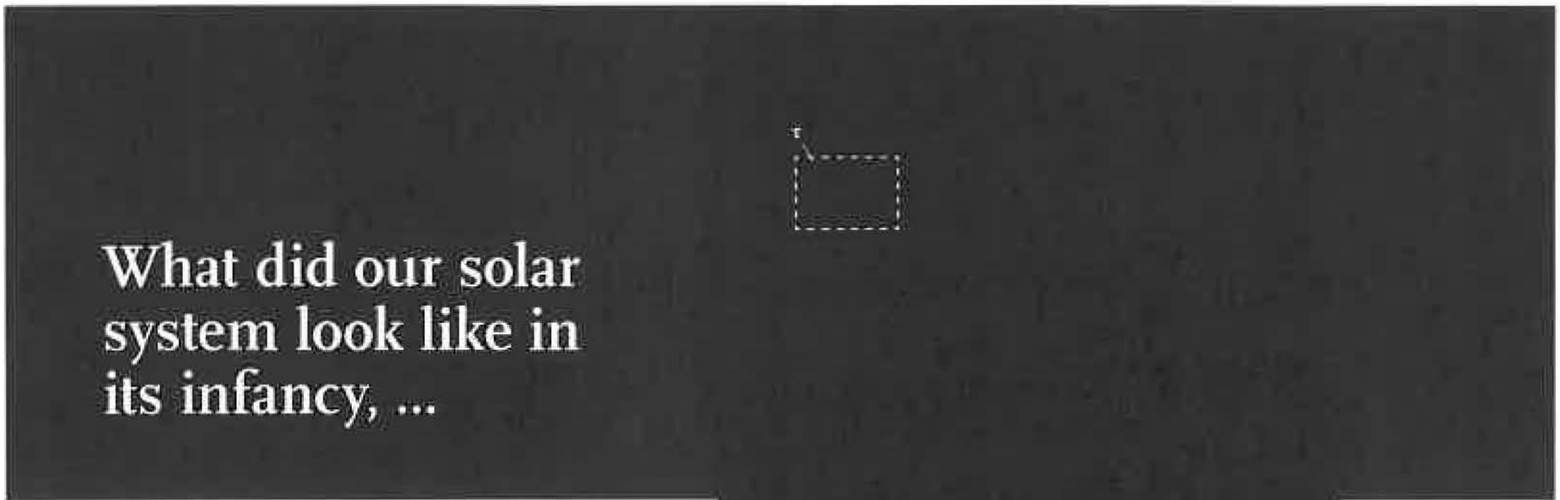
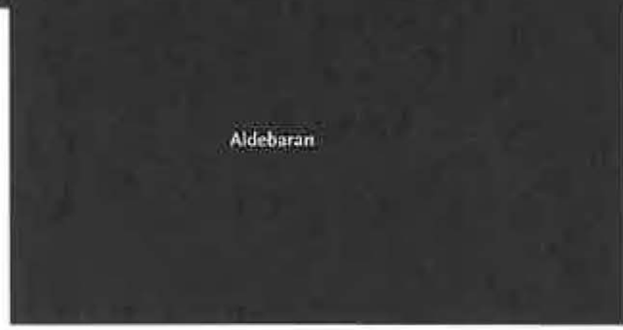
What did our solar system look like in its infancy, ...





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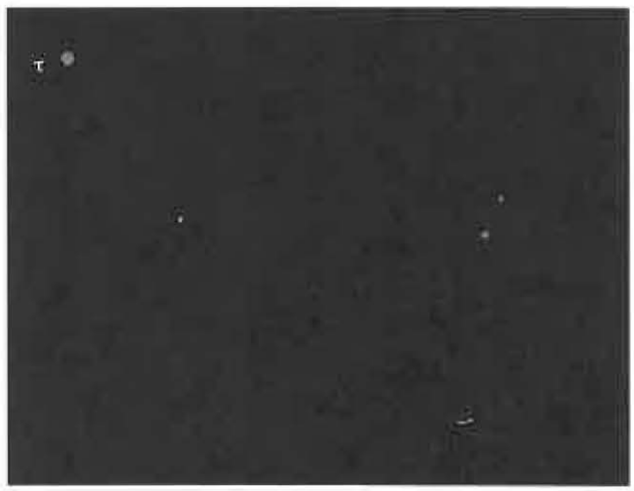
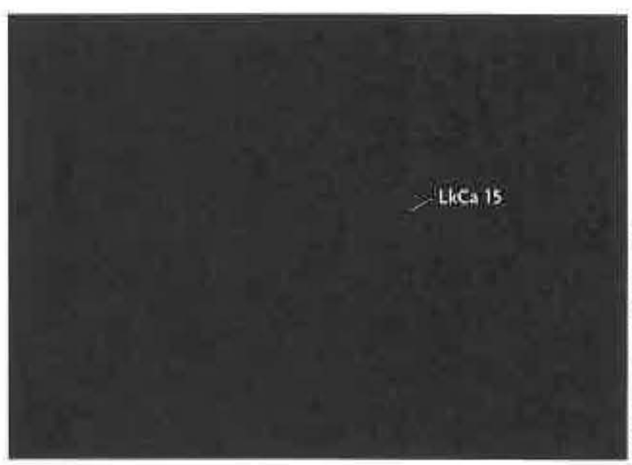
. . . when the planets were forming? We cannot travel back in time to take an image of the early solar system, but in principle we can have the next best thing: images of infant planetary systems around Sun-like stars with ages of 1 to 5 million years, the time we think it took for the giant planets to form.

Infant exoplanetary systems are critically important because they can help us understand how our solar system fits within the context of planet formation in general. More than 80% of stars are born with gas- and dust-rich disks, and thus have the potential to form planets. Through many methods we have identified more than 760 planetary systems around middle-aged stars like the Sun, but many of these have architectures that look nothing like our solar system. Young planetary systems are important missing links between various endpoints and may help us understand how and when these differences emerge.

Well-known star-forming regions in Taurus, Scorpius, and Orion contain stars that could have infant planetary systems. But these stars are much more distant than our nearest neighbors such as Alpha Centauri or Sirius, making it extremely challenging to produce clear images of systems that can reveal signs of recent planet formation, let alone reveal the planets themselves.

Recently, a star with the unassuming name LkCa 15 may have given us our first detailed "baby picture" of a young planetary system similar to our solar system. Located about 450 light-years away in the Taurus star-forming region, LkCa 15 has a mass comparable to the Sun (0.97 solar mass) and an age of 1 to 5 million years, comparable to the time at which Saturn and perhaps Jupiter formed. The star is surrounded by a gas-rich disk



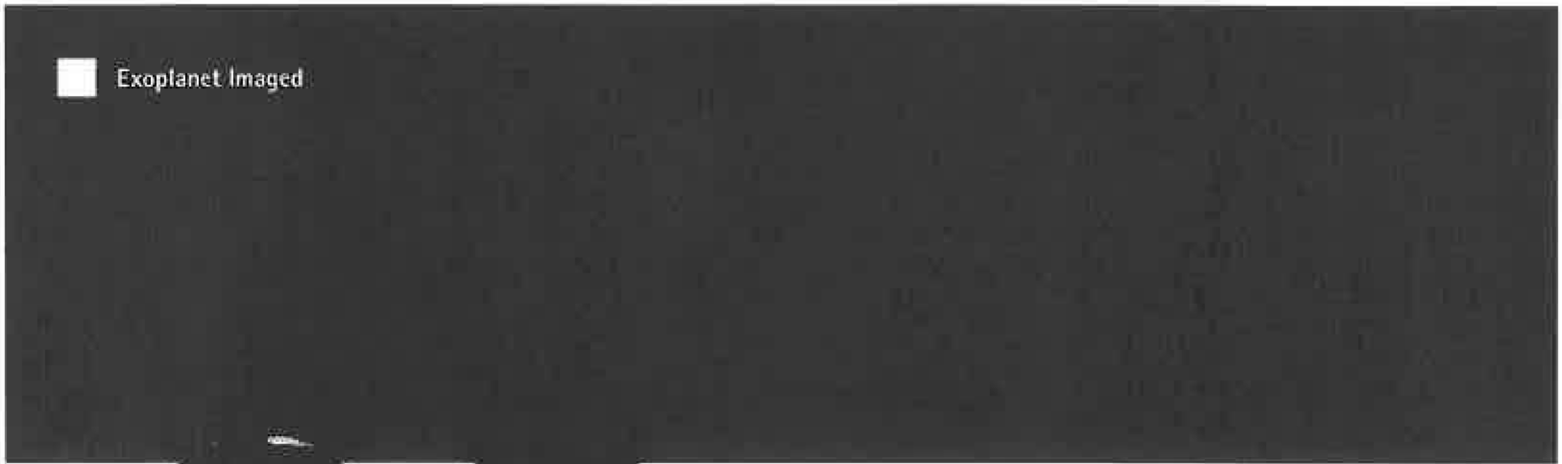


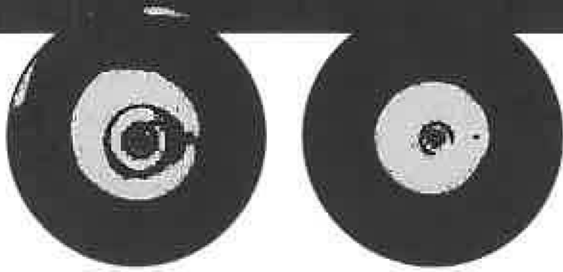
POSS-II / CALTECH / PALOMAR OBSERVATORY

BABY SOLAR SYSTEM ***Left:*** **Artist Casey Reed portrays the LkCa 15 system. The 1- to 5-million-year-old star is nearly identical in mass to the Sun and has at least one planet (foreground) comparable to Jupiter. The disk around the star has sufficient material to produce a planetary system similar to our solar system.**

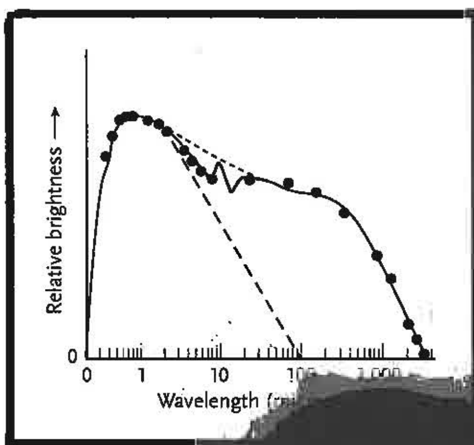
YOUNG SUN ***Right:*** **These pictures show how to find magnitude-12 LkCa 15 in Taurus at R.A. $04^h\ 39^m\ 18^s$, declination +22° 21′ 03″. It lies directly south of a magnitude-11 star. The star name comes from a 1980s Lick Observatory calcium-line survey.**

AUTHOR PHOTOS: DAVID FRIEDLANDER, NASA / GSFC





CARVING A GAP These frames from a computer simulation show how three planets (with 3 Jupiter masses each) orbiting inside a disk carve out gaps that overlap over a period of 26,667 years, creating a gap with a radius of about 15 a.u. The planets orbit the star at distances of 2.7, 6.3, and 14.3 a.u., respectively.



EVIDENCE FOR A PLANET *Left:* This spectrum shows how LkCa 15's brightness changes from visible light (0.5 to 0.8 microns) to infrared light (1 to 100 microns) to submillimeter wavelengths (100 to 1,000 microns). The short-dashed blue line ... what this plot ... if LkCa ... have a

Right: This ima... the IRAM Plat... Bure Interfero... France clearly ... the disk aroun... 15. The bright ... red regions are ... 50 astronomical ... from the star. If th... didn't have a la... the inner regio... also appear bri... orangish-red.

SEAN ANDREWS / CFA (2)

similar in structure to the one in our solar system from which the planets formed. With new technologies and observing strategies, we have confirmed suspicions that LkCa 15's disk harbors a young planetary system.

Signs of Planet Formation

Astronomers have identified LkCa 15's disk as belonging to a special subset of circumstellar disks whose members are possibly in transition from a pre-planet-building phase to a post-planet-building system. Compared to typical disks, the one around LkCa 15 (and others like it) have less mid-infrared emission. The thermal (heat) emission from circumstellar disks comes from dust heated by the central star, so the regions lacking this emission appear to be large gaps where solid materials have either been removed from the system or incorporated into larger bodies.

From the dust temperature data, models help us estimate where the dust is (and is not) located. When astronomers do such modeling, we discover that many of these disks either have cleared inner holes or large gaps separating hot material orbiting close to the star from cold material orbiting at much farther distances. In particular, studies from 2007 to 2009 led by Catherine Espaillat (Harvard-Smithsonian Center for Astrophysics) showed that LkCa 15's disk has an inner dust disk from 0.1 a.u. (its outer radius is uncertain), and an outer disk that begins at 50 a.u. — a range that would encompass all of the solar system's planets and the inner Kuiper Belt.

Theorists have predicted that young disks in the pro...s of forming giant planets will have gaps resembling ... one in LkCa 15. Massive planets affect disk structure ...xerting a tidal torque on the surrounding material. ...e planet is more massive than Saturn, the torque is ...ng enough to open a gap in the disk, which becomes ...eted in gas and presumably dust. The more massive ...planet, the larger the gap it opens in the disk.

...f left undisturbed, disk material will eventually spiral ...he way in and accrete onto the star. Because planets ... massive than Jupiter open small gaps, they don't ...ct how disk material accretes onto the star; the disk's ...er regions remain well replenished from material spi...ralling in from the outer disk. As a planet's mass increases

As massive planets such as LkCa 15b carve out gaps in disks, irregularities in the disks exert a gravitational torque on the planets. This process can cause planets to migrate substantial distances inward or outward from where they formed, helping to explain why many exoplanetary systems have Jupiter-mass planets orbiting relatively close to their host stars.

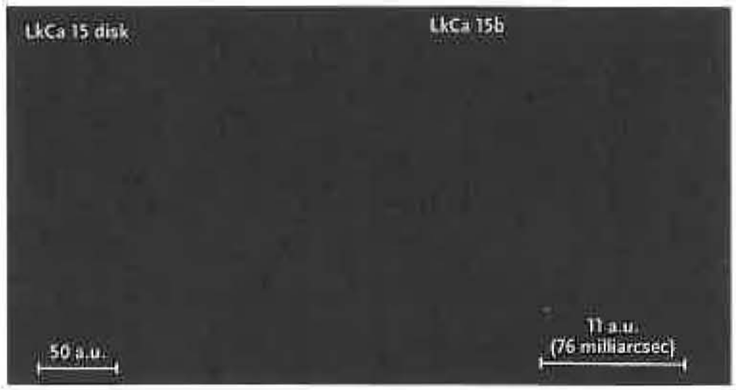
above Jupiter's, the planet intercepts more incoming gas, decoupling the inner disk from the outer disk and thus widening the gap. Objects more massive than 10 Jupiters, comparable to the most massive planets yet discovered, effectively shut off accretion onto the star, leaving a hole in the inner disk instead of a gap. A star with a low accretion rate that is surrounded by a disk with a gap (but not an inner hole) therefore provides the predicted telltale sign of an infant, actively growing Jupiter-mass planet.

Imaging an Emerging System

By 2009 it was clear that LkCa 15 exhibited strong circumstantial evidence that it harbored a young planetary system. Submillimeter observations by Vincent Piétu (Institut de Radioastronomie Millimétrique, France) and, more recently, Sean Andrews (Center for Astrophysics) and Andrea Isella (Caltech), resolved the large gap in LkCa 15's disk. In addition, the star accretes gas at a low rate compared to other stars with similar disks.

Despite these encouraging signs, confirming a young planetary system around LkCa 15 required much sharper images of the inner disk (50 a.u. and less) at wavelengths that could identify disk structure caused by unseen planets while directly ruling out stellar or brown dwarf companions. LkCa 15 had to be imaged with ground-based telescopes at near-infrared wavelengths, where the disk is bright, and with an angular resolution and contrast even better than what Hubble could provide.

TELLTALE SIGNATURE The 8-meter Subaru Telescope in Hawaii acquired this image of the disk around LkCa 15. The star itself has been masked, but its position is marked with the white dot in the center. The disk has a gap with a sharp edge, strong evidence for a planet. In addition, the center of the disk, marked with a XXXXXXXX, is slightly offset from the star.



SMOKING GUN ***Left:*** **The disk around LkCa 15.** ***Right:*** **Using the 10-meter Keck II telescope and advanced imaging techniques, Adam Kraus and Michael Ireland resolved a streamer of gas and dust (red) around LkCa 15 swirling toward a massive planet (blue) that's still forming. The planet lies about 10 a.u. from the star.**

Two main obstacles stood in the way of revealing LkCa 15's planetary system in detail. First, atmospheric turbulence blurs images, preventing us from distinguishing between a star's light and a planet's light. Second, no telescope has perfect optics: imperfections on mirror surfaces create slowly evolving, bright noise patterns known as *speckles*, which can mask the presence of planets. Fortunately, new adaptive-optics systems correct for atmospheric blurring. And even better, advanced methods of acquiring data and processing images can remove enough speckle noise to see a disk or planet surrounding a star.

The 8.2-meter Subaru Telescope in Hawaii, coupled with a new camera designed to image planets and planet-forming disks, provided even more compelling evidence. A team led by Christian Thalmann (University of Amsterdam, the Netherlands) imaged the planet-forming region of LkCa 15's disk for the first time. The team resolved the inner edge of the disk gap at 50 a.u., finding it to have a sharp edge expected if a planet is sculpting the disk. More importantly, the group found, and Isella and his

Exoplanet Imaged

Imaging young planets from ground-based telescopes is challenging because atmospheric turbulence and residual noise sources (due to imperfect telescope optics) impede our ability to separate a star's bright light from a planet's feeble glow. To overcome these obstacles, astronomers use adaptive optics to correct for most of the atmospheric blurring and then advanced observing and image-processing techniques to remove residual noise. Astronomers have incorporated these techniques to image planets around Beta Pictoris and HR 8799, which lie at separations several times the telescope's diffraction limit. Another option, non-redundant masking (NRM) interferometry, allows us to image very young and relatively bright planets at extremely small separations from the star (on the sky), at the telescope's diffraction limit.

In NRM, astronomers place a mask in front of the camera, allowing light from the star (and any planet) to pass only through a series of small holes. Instead of an image, the camera records the interference patterns from light passing through the different holes. If the holes are spaced such that the baseline (the separation from any one hole to any other) never repeats, we can use sophisticated algorithms originally developed for interferometers to reconstruct an image of the system (without having "seen" it) where the spatial resolution of the image approaches the theoretical (diffraction) limit. That's good enough to reveal the planet. In the case of LkCa 15b, Adam Kraus and Michael Ireland also took calibration images of other nearby stars to remove residual effects resulting from imperfect image quality.

Because light can pass through only a small

team have confirmed, that the gap is slightly offset relative to the star, strong evidence for an unseen companion. If a low-mass stellar or brown dwarf companion were responsible for this offset, Thalmann and his collaborators would have detected it, but they didn't.

Last October, Adam Kraus (University of Hawaii) and Michael Ireland (Macquarie University, Australia) reported a direct detection of a planet in the disk gap of LkCa 15. Using the 10-meter Keck II telescope, Kraus and Ireland employed an additional technique known as NRM, short for non-redundant masking (NRM) interferometry (see "Imaging Young Exoplanets," above). NRM provides a way to separate the light from a star and extremely luminous planets at small separations. Kraus and Ireland initially detected the companion in 2009 at a tiny separation of about 75 milliarcseconds (a Saturn-like 10 a.u. at 450 light-years distance) from the star. Observations in 2010 detected the planet at roughly the same location. Because LkCa 15's space motion is known, they compared the companion's position to what it would be if it were an unrelated background object and concluded it's a gravitationally bound object consistent with being a planet.

An Infant Planet

Looking at the image of LkCa 15b, it's a bit hard to see the face of the planet it will become, because the infant planet's appearance stands in stark contrast to those of adolescent planets recently imaged around Beta Pictoris and HR 8799 (12 million years old and 30 million years old, respectively). These planets appear as unresolved point sources, but the emission identifying the planet around LkCa 15 appears as a slightly elongated blob, indicating that it originates from a region far larger than the diameter of a fully formed giant planet. Furthermore, the emission comes not from one structure but two: a centrally located blob clearly detected at 2 microns and a pair of lobes detected at 3.8 microns, located at roughly the same distance from the star as the central source but leading or trailing it in orbit.

LkCa 15b's complex structure requires explanations beyond simply reflected light or thermal emission from a spherical, Jupiter-sized object. Kraus and Ireland interpret the lobes to be material falling along a streamline toward the central source, which presumably marks the planet itself. Thus, in further contrast to imaged planets around Beta Pictoris and HR 8799, we see LkCa 15's infant planet indirectly, since we're actually catching gas and dust heated as it falls toward a shrouded central object (the planet itself).

The planet's odd appearance presents additional problems in constraining its physical properties. For example, gas giants contract and cool in a way quantified by detailed planet-evolution models. Thus, the luminosities of planets

MORE DISKS WITH GAPS These three images of planet-forming disks around young stars, taken with the Submillimeter Array interferometer, show clear signatures of large gaps inside the red areas, strong indicators of forming planets. In some cases, we see the disk from the side, which leads to double-peak structures that appear as two reddish regions. SEAN ANDREWS / CFA (3) number of holes, the effective light collecting area of a telescope in NRM mode is much less than in normal imaging. Consequently, NRM can right now help us detect only the brightest exoplanets, and it has so far failed to provide images of the previously detected Beta Pic and HR 8799 planets, which are significantly fainter than LkCa 15b. But since planets are brightest when they are newly formed, NRM is well suited for imaging 1- to 5-million-year-old giants such as LkCa 15b.

such as Beta Pictoris b and the four known HR 8799 companions can yield estimates for the objects' masses. Estimating LkCa 15b's mass from its luminosity is trickier, because the infant planet's age uncertainty (1 to 5 million years) translates into a much larger mass uncertainty than for Beta Pic b and the HR 8799 companions because planets cool very rapidly right after their formation.

More importantly, the light identifying the planet likely comes from more than just the planet itself; it probably includes emission from accreting material. So even if we knew LkCa 15's age to high precision, it's very difficult to estimate the planet's luminosity and use this characteristic to estimate the planet's mass. But the total luminosity of the central source and the lobes is significantly less than the luminosity of young 10- to 20-Jupiter-mass objects, so the planet's heft is probably less than 10 Jupiter masses. If the planet is responsible for the gap, which is likely, then disk models predict that its mass should be at least 1 Jupiter. The planet is thus likely comparable in mass to Jupiter or is a slightly scaled-up version of it.

The First of Many Baby Pictures

Although LkCa 15's disk and infant planet provide an important first picture of a baby solar system, we may not have identified all the massive planets in the system. Recent studies by Zhaohuan Zhu (Princeton University) and Sally Dodson-Robinson (University of Texas, Austin) indicate that the LkCa 15 disk gap is too large to be carved by just one giant planet. We have yet to image a second planet in the gap, but such a planet would further cement LkCa 15's status as a young solar system analog, because our own solar system has two gas giants.

Even more encouraging, LkCa 15 is probably not the only newborn Sun-like star that harbors an infant planet that we can image. A number of researchers, including Catherine Espaillat and Kyoung Hee Kim (University of Rochester), have identified many nearby stars that are about the same age as LkCa 15 and that are also surrounded by disks that show signs of having large gaps consistent with forming planets. Submillimeter imaging by Sean Andrews (Center for Astrophysics) and David Wilner (University of Hawaii) shows that some of these disks have gaps extending from 10 to 50 a.u., encompassing the gas- and ice-giant planet regions in our solar system. They also exhibit structures that seem to indicate massive planets.

A team lead by Nuria Huélamo (Centro de Astrobiología, INTA-CSIC, Spain) using the Very Large Telescope in Chile may have already detected a low-mass object in the disk gap of another Sun-like star, T Chamaeleon: perhaps another young solar system analog. These new observations give us confidence that soon our single image of an emerging planetary system will be joined by pictures of many other systems, comprising a nursery of young solar system analogs that will better clarify our own solar system's evolution within the range of planet-formation sequences and outcomes. ✦

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