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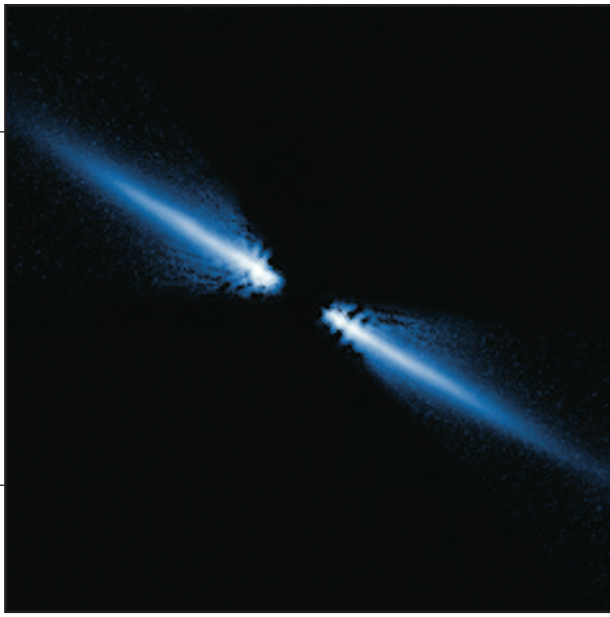

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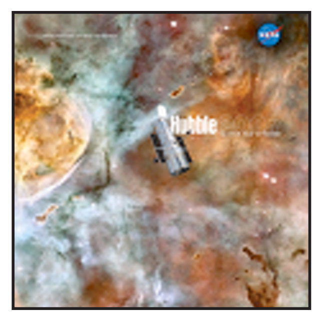

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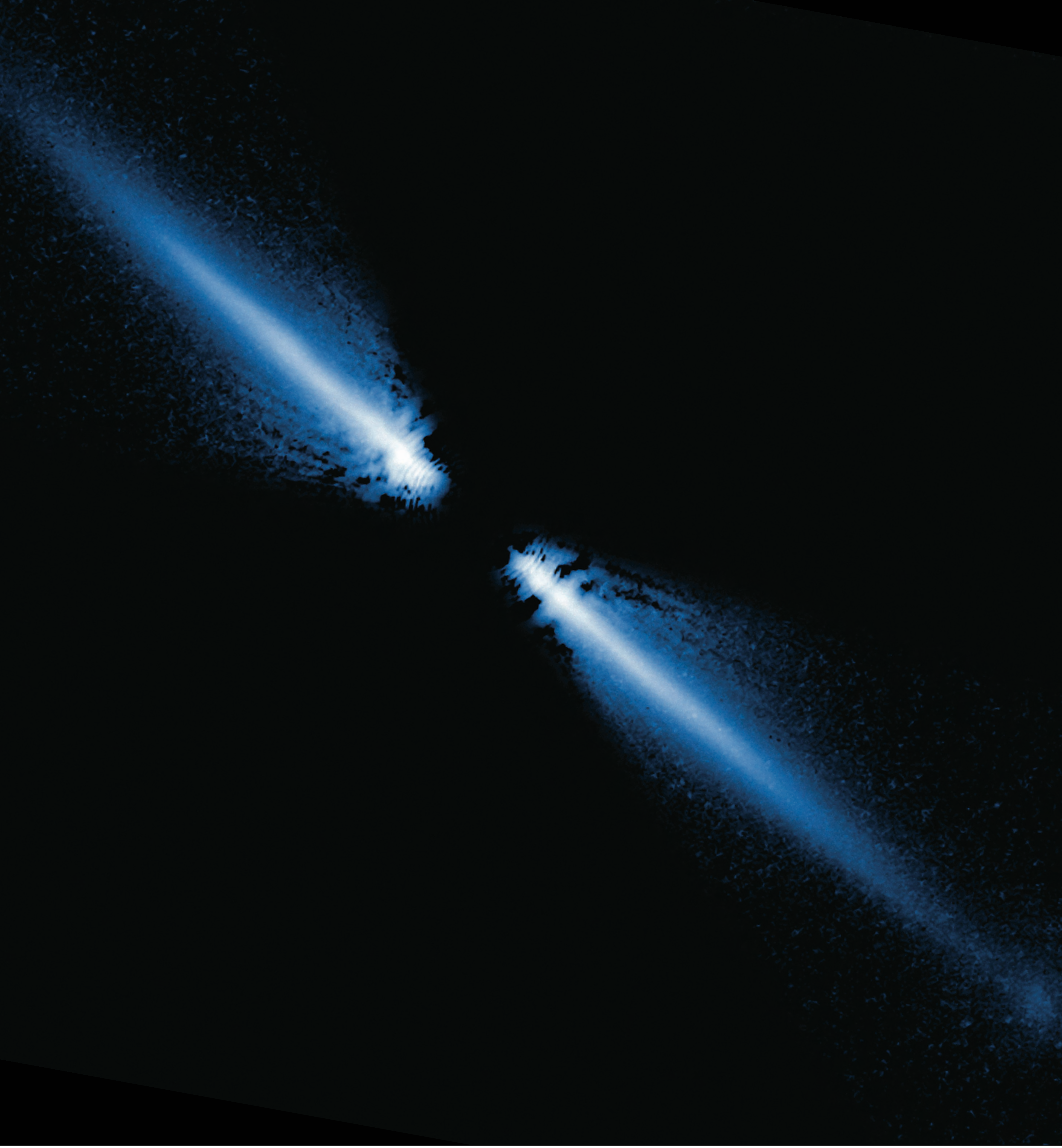


Planets in a Sandbox: *Hubble*'s Renaissance of Debris Disk Imaging

Paul Kalas

Conduct a search for "false dawn" in the *New York Times* or Google Books Web sites, and you might conclude that this is political parlance for a promising social policy that ultimately fails. To a stargazer, however, the phrase refers to a faint glow visible right before "true" dawn, called "zodiacal light." Under superb conditions, the band of zodiacal light can be seen all the way around the sky, following along the path of the Sun and planets as they progress through the 12 divisions of the zodiac. The zodiacal light is actually a reflection of sunlight. The reflectors are billions of dust grains, many times the size of sand, orbiting between the planets in the plane of our Solar System.

If the zodiacal light can be seen by the naked eye, then this is hardly a worthwhile target for the *Hubble Space Telescope*. Yet it is one of the most challenging things to observe with *Hubble*, or any telescope, when you are looking for it around other stars. The challenge arises because the faint light reflecting from dust grains around other stars is many thousands of times fainter than the star. Basically, it is the same problem of contrast that we have when searching for reflected light from planets around other stars. It's not that our telescopes do not have the necessary sharpness or angular resolution, but rather the light from the star is much brighter than that from an exoplanet or exo-zodiacal dust cloud. Essentially, the signal that we want to detect is swamped by the noise produced from the star itself.

This is not so at infrared wavelengths. The energy emitted by a relatively hot star peaks at visible wavelengths, but tails off toward longer wavelengths. It is exactly at these longer wavelengths, however, that the infrared emission of heated dust grains has its peak.

Extending outward in a broad, flat plane seen edge-on is a debris disk around the star AU Microscopii (AU Mic). AU Mic is a red dwarf star located approximately 30 light-years from the Sun. Light from the star itself is masked instrumentally behind the dark central portion of the image.

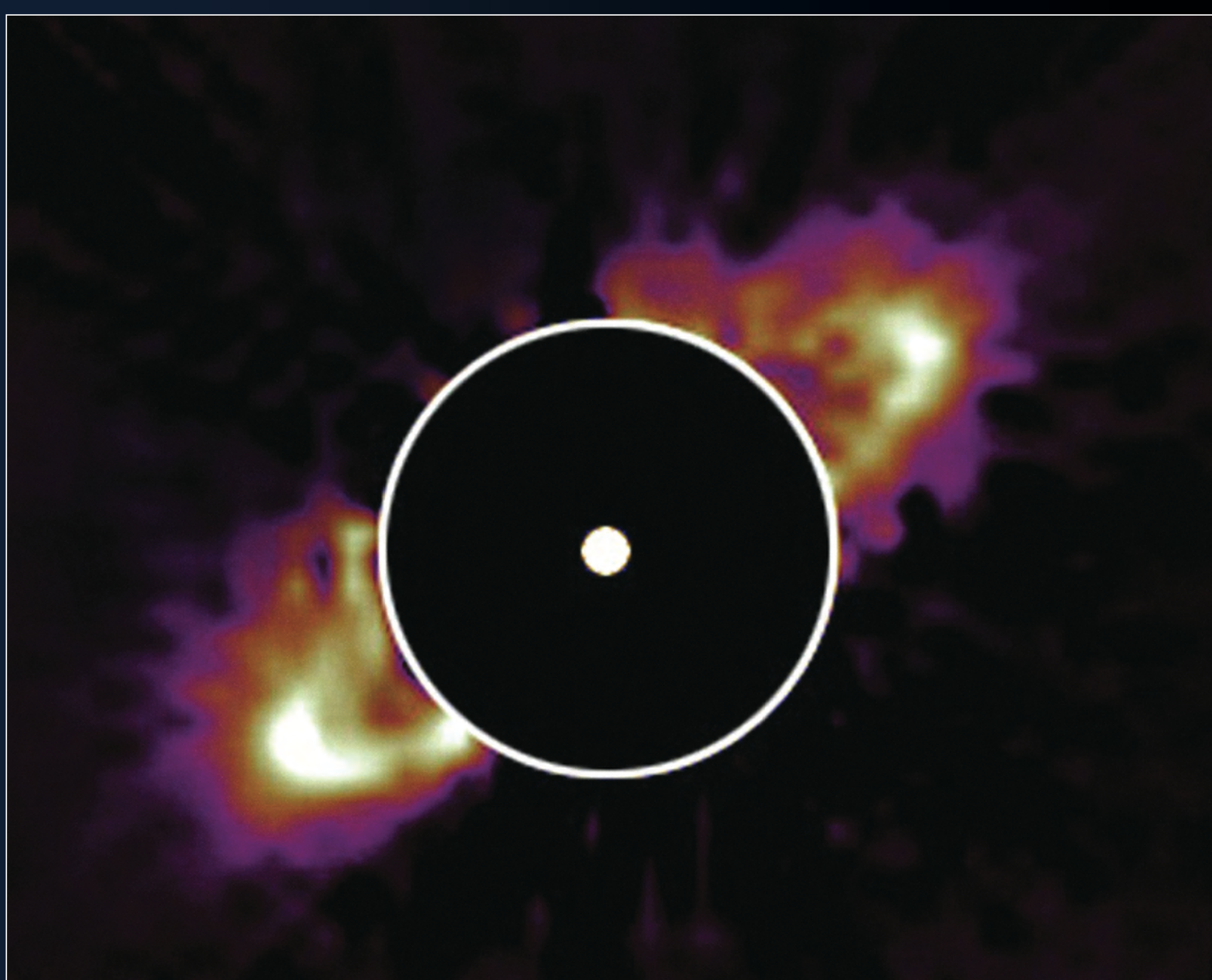
The zodiacal light is a faint, triangularly-shaped glow seen with the naked eye from dark locations on Earth. It appears to extend up from the vicinity of the Sun along the ecliptic or zodiac. In this photo, taken by the author, Comet Hale-Bopp can also be seen in the upper right. (Photo credit: P. Kalas)

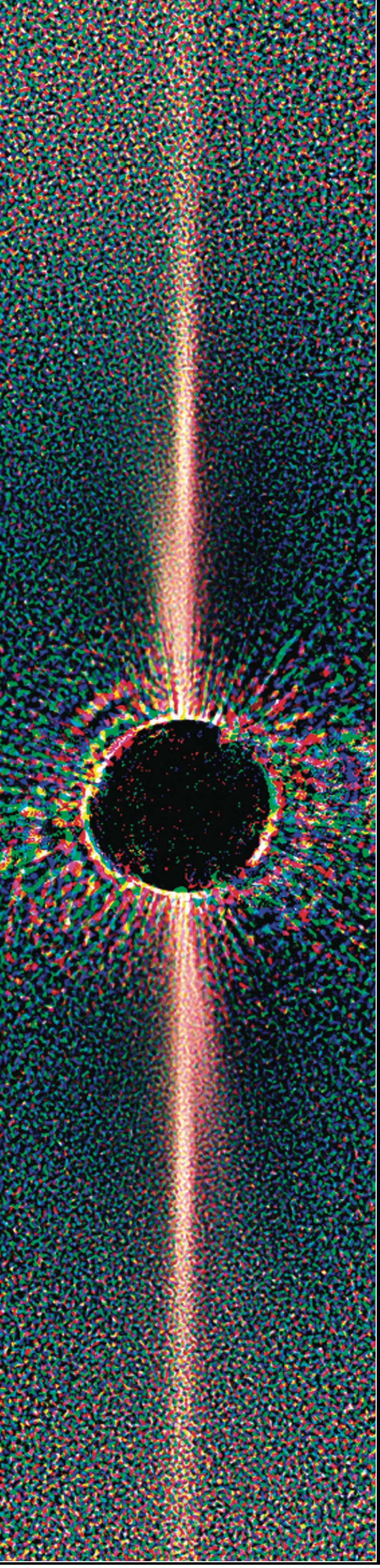
When NASA launched the *Infrared Astronomical Satellite* (IRAS) in 1983, a renaissance began. Starting with the bright star Vega, star after star was found to have extra emission at infrared wavelengths due to orbiting dust grains. In those years, the discovery of exoplanets was still a decade away; thus, the dust that circled Vega and roughly 100 other stars was the first compelling evidence that other stars have solid bodies in orbit around them.

Moreover, astronomers calculated that the lifetime for a star-orbiting dust grain is typically shorter than the lifetime of its star; thus, the system's dust had to be replenished from somewhere. That reservoir was identified as a population of comets and asteroids around other stars, much like the ones we observe in our Solar System.

Yet the direct imaging of reflected light from the dust grains vexed astronomers for several decades afterwards. One star—Beta Pictoris (Beta Pic), a bright star in the Southern Hemisphere—revealed a disk-like nebulosity, but not Vega, or Fomalhaut, or hundreds of other stars that had infrared excess. Because the Beta Pic images showed that the dust circling the central star is confined to a flattened disk (as opposed to a spherical cloud), we call these objects "circumstellar dust disks." Another term often used is "debris disk," because the origin of the dust is the collisional erosion of comets and asteroids.

Viewed at red and infrared wavelengths, the star HD 4796A is clearly seen to possess a structured ring of surrounding dust. The ring is a thousand times fainter than the star, requiring a special occulting element (black circle with white dot) to mask the star in order to be seen. HR 4796A, located approximately 220 light-years away, is visible to the naked eye as a faint speck in the southern constellation of Centaurus.





Fifteen years later, a new camera installed aboard *Hubble*, called the Near-Infrared Camera and Multi-Object Spectrometer, revealed a tiny ring of material around the star HR 4796A. Resembling the rings of Saturn, HR 4796A confirmed what astronomers had inferred all along—the dust surrounding stars can be confined to rings, possibly by the gravitational perturbations of planets. Though not seen directly, these planets could reveal their presence by their gravitational tug on the system of dust grains.

The renaissance of imaging debris disks would have to wait until astronauts upgraded *Hubble* with the Advanced Camera for Surveys (ACS) in 2002. Among the ACS's suite of new capabilities was a special device called a coronagraph. Originally intended to artificially eclipse the Sun to observe the faint solar corona, a coronagraph can also be used at night to block out individual stars in order to observe the environment around them. What ACS instrument scientists had in mind was to search for faint companions and circumstellar dust disks around the multitude of bright, nearby stars that had evidence of solid material in the infrared spectrum.

True to its purpose, in 5 years, the ACS coronagraph delivered twice as many new detections of dust disks in reflected light as had been obtained in 15 years prior. Why, however, was this sharp increase in disk discoveries important?

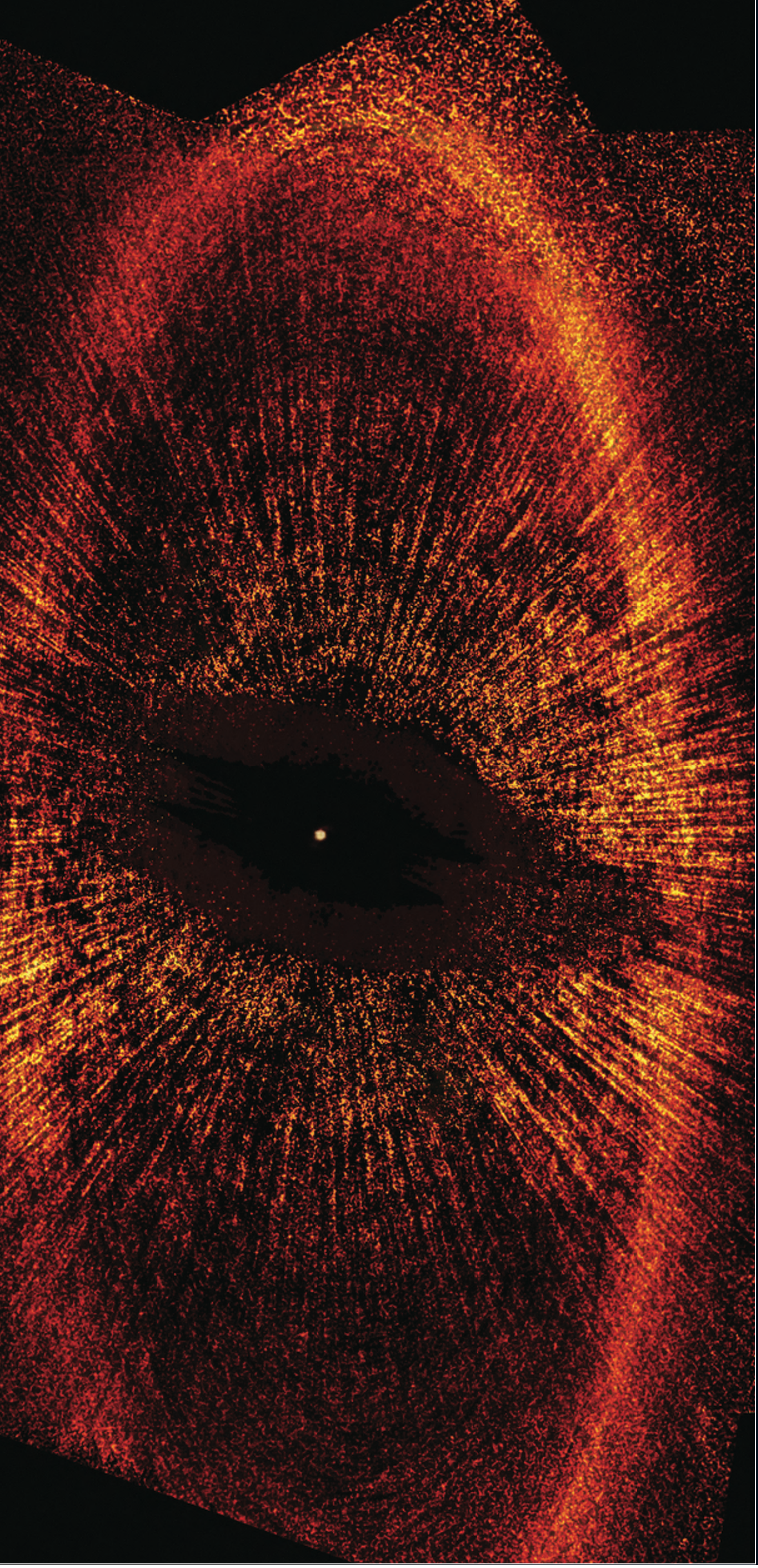
Previous research on the Beta Pic debris disk revealed a multitude of new and unexpected characteristics, such as a highly asymmetric shape. If you wanted Saturn's beautifully symmetric rings to look like Beta Pic's dust disk, you would have to twist the rings a bit, stretch one side outward by 25%, and make sure the short side always looked fatter than the long side. These unexpected findings puzzled astronomers for over a decade. Were these distortions in the Beta Pictoris disk common, or unusual, among planetary systems? In a related question, is our Solar System, with a relatively neat collection of planets, one with liquid water, a very rare or a very common system?

Imaged here is the large debris disk extending to either side of the star Beta Pictoris, the second brightest star in the small constellation of Pictor. The multicolored areas surrounding the black disk of the instrument that blocks the star itself, are imaging artifacts.

The discovery of the first extrasolar planet in 1995 stunned astronomers into accepting that previously unimaginable planetary diversity was possible. The planet around 51 Peg is similar in mass to our Jupiter, but its orbital radius from the star is less than the distance of Mercury from the Sun. In 2007, however, after cataloging over 200 extrasolar planets, we know that 51 Peg falls into a class of planetary systems where a Jupiter-like planet formed very far out, and then migrated to a very short distance from the star because of drag forces suffered between the planet and the disk of gas and dust surrounding a young star. Only 6% of stars actually have a Jupiter-like planet in an orbit much like our own Jupiter, and some of the latest results pinpoint the existence of planets around other stars that are more like Saturn, and some resemble very massive versions of Earth.

So, too, the *Hubble* ACS coronagraph created a new catalog of debris disks that could attack the question of whether or not our Solar System was extraordinary or run-of-the-mill. One fundamental advance is that previous to *Hubble*'s ACS, we only had images of debris disks surrounding massive A-type stars, such as Beta Pic (75% more massive than the Sun). Such massive stars consume their fuel quickly and die out in 1 billion years. Naturally, we are more curious about stars that could live as long as the Sun with a stable planetary system amenable to life. Thanks to ACS, we now have images of debris disks around stars of every spectral type, including some stars similar to the Sun. The new *Hubble* images show that all of the debris disks have central zones that are relatively dustless. The dust-free zones typically extend 30–50 AU in radius from the star (1 AU, or Astronomical Unit, is the distance of Earth from the Sun). In our Solar System, the Kuiper Belt extends outside the planetary region defined by the orbit of Neptune at 30 AU. It is very hard for Kuiper Belt objects to penetrate this perimeter and survive because their orbits will be highly perturbed as soon as they encounter one or more of the planets.

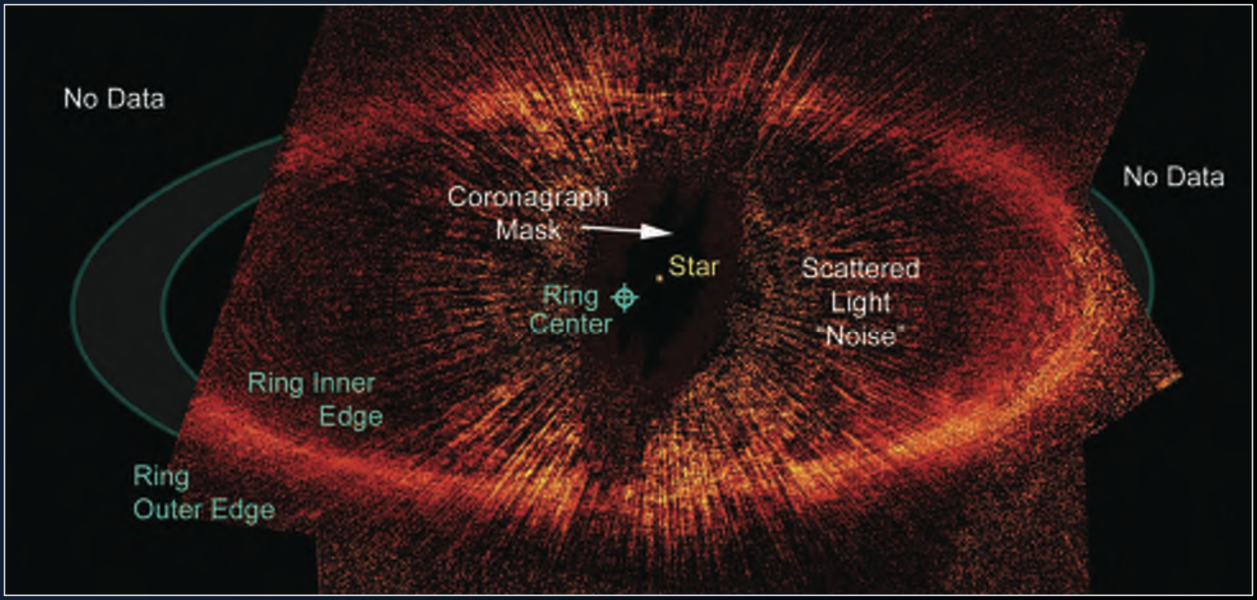
Could the central dustless zones detected in the new debris disk images also be caused and maintained by planetary systems around these stars? In many cases, this seems to be the most likely explanation, though others exist. For example, just like a mountain has a snowline above which the temperatures are cold enough that snow survives on the ground, at some radius from a star, the temperatures are cold enough that icy bodies survive a very long time. A disk composed of icy grains would naturally have a hole cut out of it where temperatures are too hot for icy grains to exist. However, this alternate

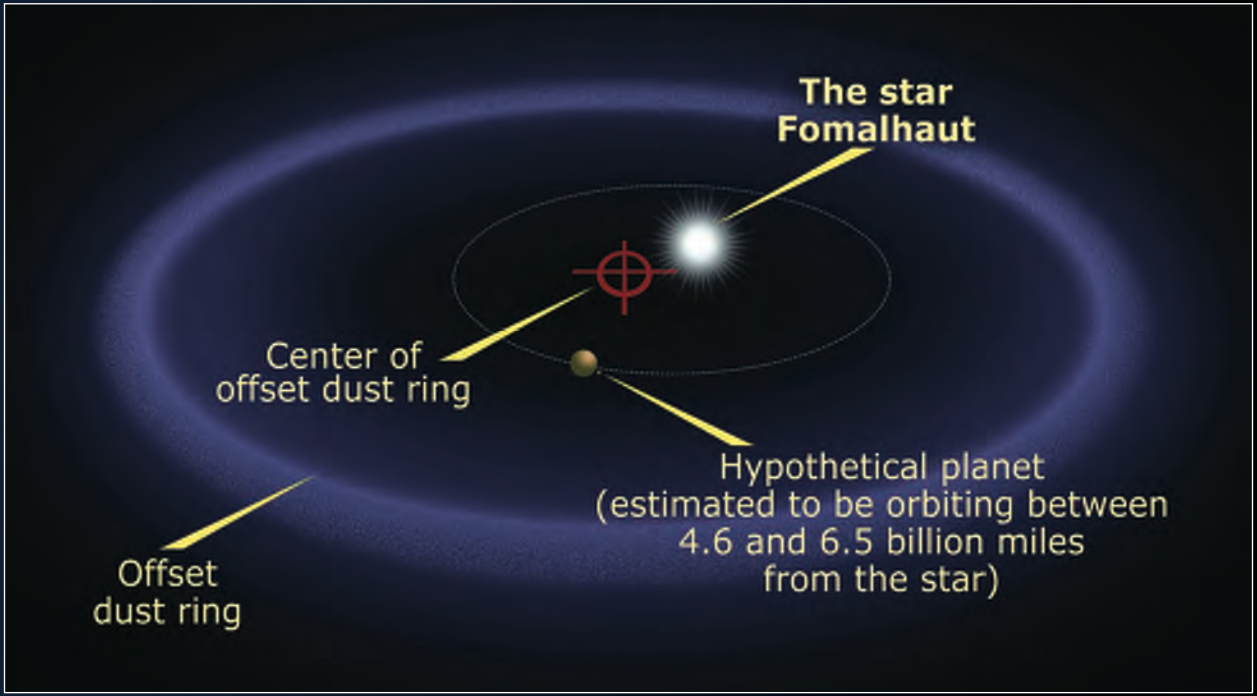


explanation does not work for the disk around AU Microscopii—one of the first new debris disks imaged with *Hubble*. ("AU" here is part of the star's name—frequently shortened to AU Mic—it is not an abbreviation for "Astronomical Unit.") AU Mic is a red dwarf, with a mass half that of the Sun, and a snowline that is near 1 AU—yet the dustless perimeter goes out to about 30 AU. But if planets are clearing out the dust from AU Mic's central region, why haven't these planets been detected by the doppler method (back-and-forth wobble of the star caused by the gravitational tug of an orbiting planet), which first revealed the planet around 51 Peg?

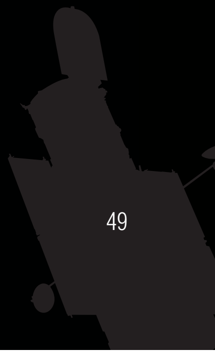
The general problem is that the central dust clearing can be created by smallish planets, like Neptune, which are difficult to detect with doppler surveys. For example, an extrasolar "Neptune" 30 AU from a Sun-like star would require at least 50 years of continuous monitoring in order to detect the doppler signal. Fortunately, just eight months before the ACS power supply failed, astronomers imaged a debris disk around a star already known to have an extrasolar planet. HD 10647 is a Sun-like star with a "Jupiter" at a radius of 2 AU. The debris disk occupies a region between 75 and 120 AU radius from the star. The much larger size of the debris disk suggests that beyond the known "Jupiter" at 2 AU, HD 10647 may have at least one "Neptune," which clears out the region between 2 AU and 75 AU radius.

Debris disk around the star Fomalhaut.





Surrounding the bright autumn star Fomalhaut is the best known example of a debris disk ring with a cleared central zone. *Hubble* unequivocally shows that the center of the ring is offset from the star. The most plausible explanation is that an unseen planet moving in an elliptical orbit is reshaping the ring with its gravitational pull. The scattered light noise in the upper image is residual starlight bleeding past the coronographic mask that is designed to block the light of the star. A small white dot labeled "Star" indicates the position of the star behind the mask.



Probably the clearest example of a debris disk with a central clearing zone and evidence for planets is Fomalhaut, a bright autumn star in the Northern Hemisphere. From the IRAS infrared data, we knew all along that it had dust around it, but the star was simply too bright to achieve the detection of the fainter dust component. Calculations showed that imaging the disk with ACS would also be impossible. Yet in 2005, when we artificially eclipsed Fomalhaut with ACS to search for Jupiter-like planets, a faint ring of dust appeared, as if emerging from a 20-year-old fog. The *Hubble* image of Fomalhaut's dusty ring, 100 million times fainter than the star, represents the ultimate limit of our current detection technology at optical wavelengths. Because Fomalhaut is only 25 light-years from us, the ring has a large angular extent on the sky. Because of this, the northeast side of the ring has yet to be imaged, as it falls outside the field of view of the ACS coronagraph. Perhaps the most surprising finding is that the geometric center of the ring does not fall nicely on the star, but 15 AU to one side. Theoretically, this is possible if a planet has an eccentric orbit (i.e., not perfectly circular) where the star lies at one focus of the ellipse tracing the orbit. The planet's gravity slowly alters the orbit of each particle in the dust ring, with the end result being that the ring is off-center relative to the star.

This artist's concept depicts a distant hypothetical solar system, similar to our own. Looking inward from the system's outer fringes, a ring of dusty debris can be seen, and within it, planets circling a star the size of our Sun. (Image credit: NASA/JPL-Caltech/T. Pyle, SSC)

To summarize, in contrast to a "false dawn," recent *Hubble* observations have led to a true dawn—a real renaissance—in the study of debris disks. The ACS coronagraph has detected the reflected light from dust disks and rings surrounding other stars where other telescopes have failed to do so. These disks have features that appear to be closely related to the Solar System's zodiacal light and Kuiper Belt. The correspondences strongly suggest that the Solar System is not unusual, but must have many close analogs in the universe, even around nearby stars. If the next *Hubble* servicing mission is able to repair the ACS, then a few additional years of operation will certainly continue the renaissance. For the time being, the renaissance in debris-disk imaging will continue with the new generation of ground-based instruments that will target the dozen or so debris disks first seen with ACS.

Paul Kalas is an Assistant Adjunct Professor of Astronomy at the University of California, Berkeley. Prof. Kalas was born in New York, raised in Michigan, and earned his doctoral degree from the University of Hawaii. His research programs primarily utilize the *Hubble Space Telescope*, Keck Observatory, and the Very Large Telescope, with additional programs conducted with the Gemini Observatory, the *Spitzer Space Telescope*, Lick Observatory, and the James Clerk Maxwell Telescope. Among his accomplishments are the optical discoveries of debris belts surrounding the nearby stars Fomalhaut and AU Microscopii. Kalas' coronagraphic observations of nearby stars represent the largest database of its kind.