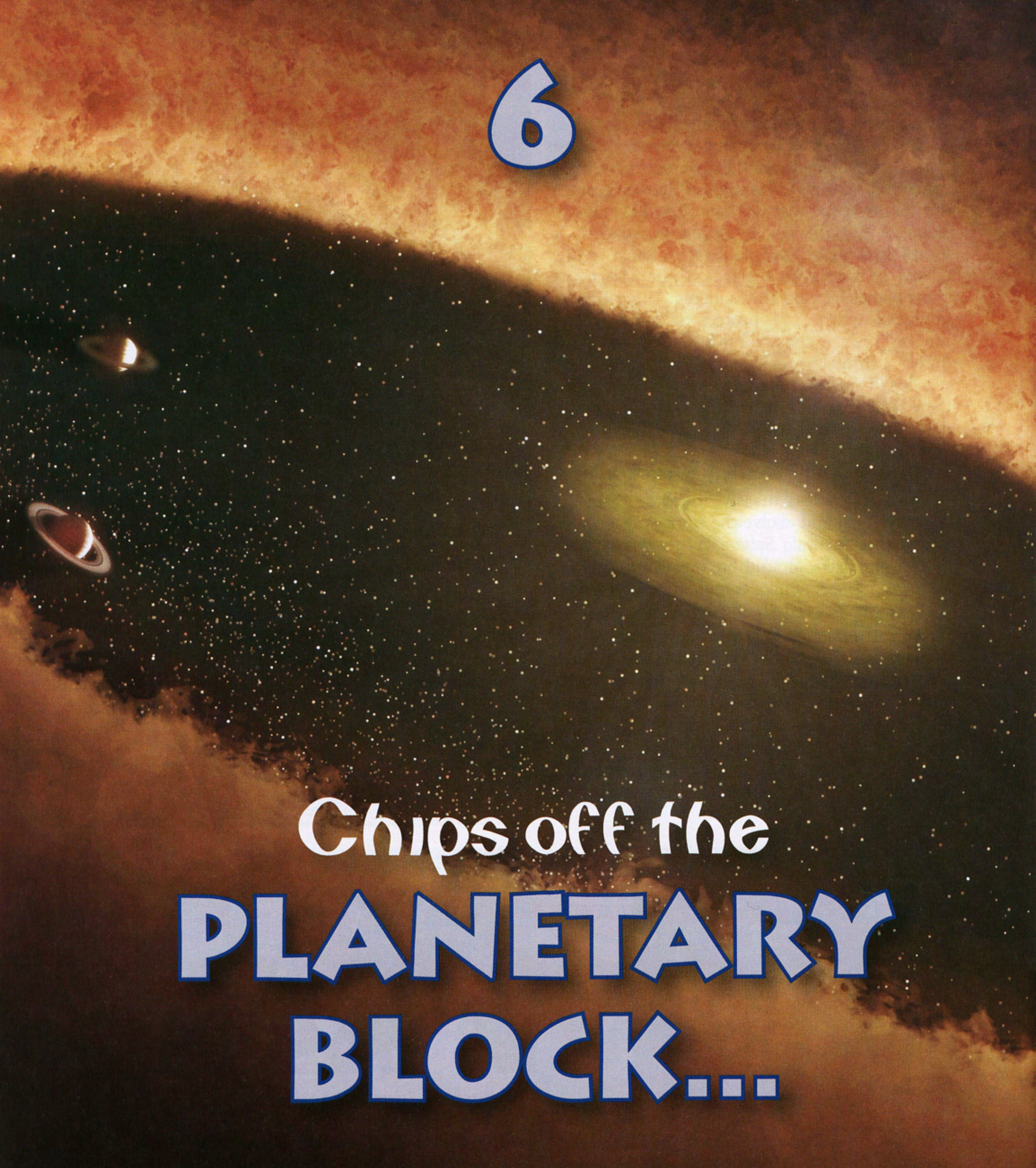


6

Chips off the PLANETARY BLOCK...

Star formation and planetary disk formation go hand in hand. Here, astronomers *James R. Graham* and *Paul Kalas* both from the University of California, Berkeley, explore the fascinating details astronomers are now discovering about the formation of debris disks that linger after the formation of a solar system.

Image courtesy NASA/JPL-Caltech/T. Pyle (SSC/Caltech).

...Building Planetary DEBRIS DISKS

The Zodiacal Light: *Our Own Debris Disk*

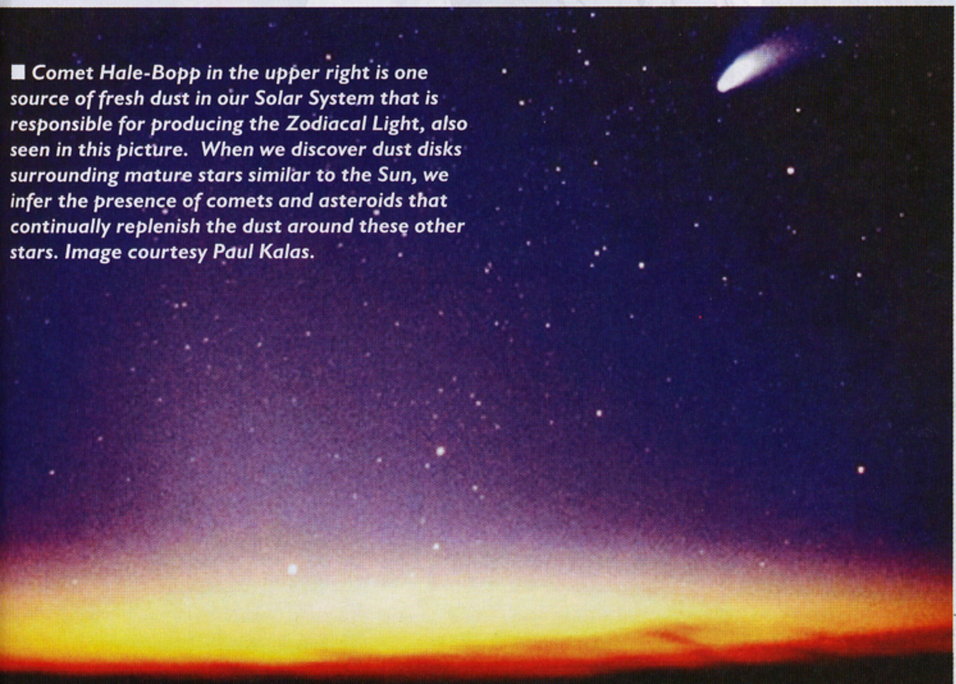
IN OUR own Solar System primitive bodies, such as comets and asteroids, are continually being eroded, releasing puffs and tails of debris, seeding interplanetary space with tiny dust grains. Born within the thin plane containing most of the solid mass orbiting the Sun, the trillions of dust grains form a tenuous, flattened cloud called a circumstellar disk. If gravity were the only force acting on these grains, then they would continue to orbit the Sun. However, various small but persistent influences, including radiation pressure from the Sun and drag forces, either cause grains to spiral inward to the Sun or blow them out to interstellar space. No worries. Asteroids and comets continue to fill the depleted debris disk with fresh grains. From our perspective on Earth, this dust is visible as the faint band of zodiacal light or the 'false dawn.' This is sunlight reflected from transitory dust in the plane of the Solar System.

The zodiacal light has been known since antiquity, but its counterpart for other stars was first seen in the early 1980s. Early clues to the existence of extrasolar dusty debris disks were found by George Aumann using the Infra-Red Astronomical Satellite (IRAS), which discovered that a handful of familiar, nearby A-type stars (stars with surface temperatures of 10,000 K), such as Vega and Fomalhaut, had orbiting dust clouds.

Seeing the zodiacal light is difficult – it can only be viewed on the darkest, moonless nights far away from the light pollution of cities. Imagine how hard it is too see the zodiacal light around other stars! In the 1930s French astronomer Bernard Lyot invented a special type of instrument for telescopes called a coronagraph to produce artificial eclipses of the Sun to permit routine observations of the tenuous solar corona. Shortly after the IRAS discovery, Brad Smith and Richard Terille used a coronagraph to show that the dust around Beta Pictoris was confined to a thin disk, and clearly analogous to the zodiacal dust in our own Solar System.

Ultimately, IRAS found that about 15 percent of all A-type stars have debris disks. Therefore, if debris disks arise from the erosion of larger bodies this was among the first hints that planetary systems are common.

The liquid helium cryogen for the IRAS satellite ran out on 21 November 1983, after



■ *Comet Hale-Bopp in the upper right is one source of fresh dust in our Solar System that is responsible for producing the Zodiacal Light, also seen in this picture. When we discover dust disks surrounding mature stars similar to the Sun, we infer the presence of comets and asteroids that continually replenish the dust around these other stars. Image courtesy Paul Kalas.*

■ *This artist's concept depicts a hypothetical solar system, similar in age to our own. Looking inward from the system's outer reaches, a dust ring of debris can be seen. Further in, planets orbit a yellow G-type dwarf much like our sun. The debris is the relic of a disk of gas and dust from which planets grew. Small dust grains are removed by various forces, including radiation pressure and the effects of the solar wind, but collisions between larger bodies and evaporation of comets that wander too close to the star continually replenish this material. Image courtesy T. Pyle, NASA/JPL-Caltech/Spitzer Science Center.*

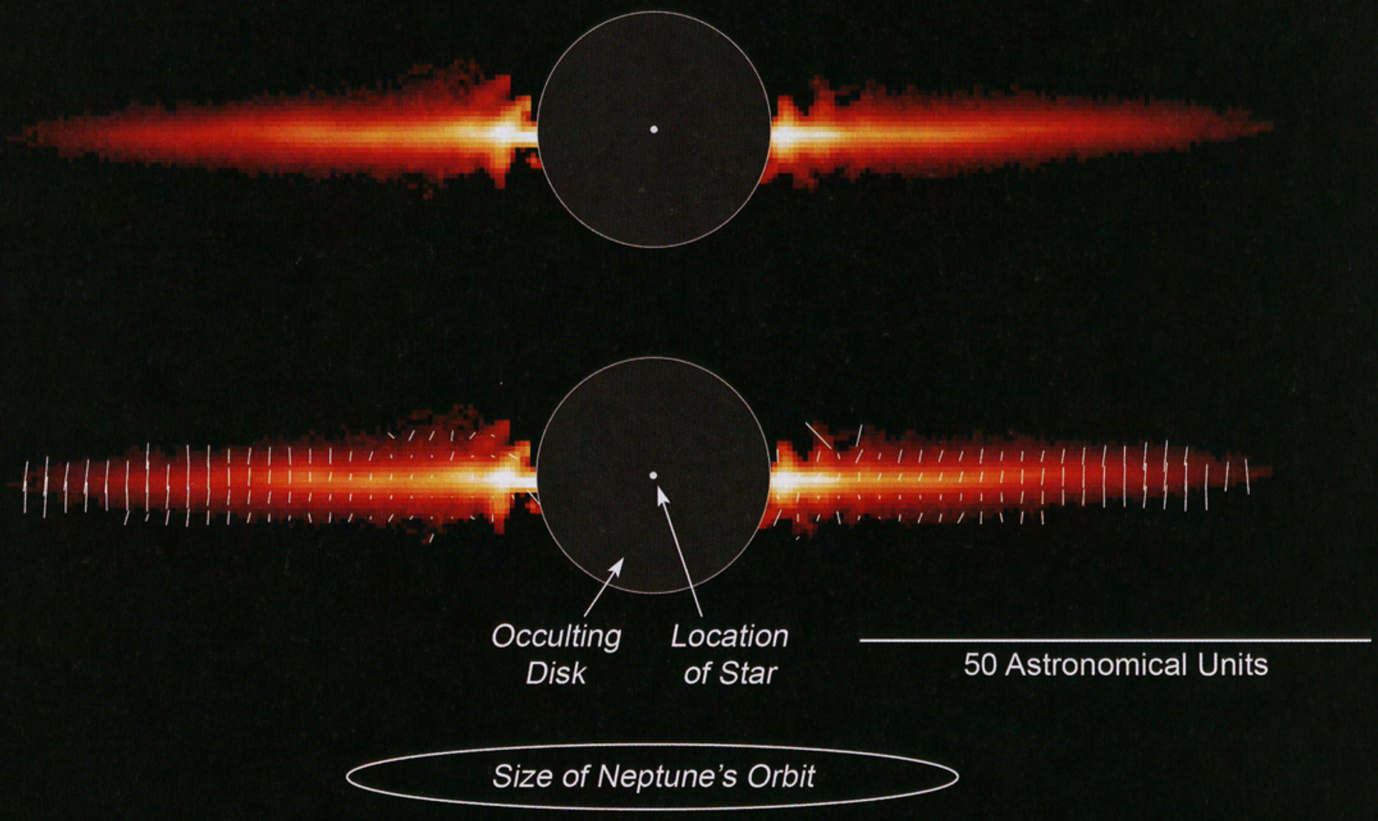
nearly ten months of operation. However, the IRAS archival data have continued to be mined for neglected stars. As recently as 2004, a red dwarf sibling of Beta Pictoris, AU Microscopii, which was first detected by IRAS, was shown to have a prominent debris disk. The list of debris disks now includes many famous names, including Beta Pictoris, Vega, Fomalhaut, Epsilon Eridani, Tau Ceti, and Eta Corvi. Many more are now known, but are referred to merely by their entries in the 19th century star catalog of Henry Draper.

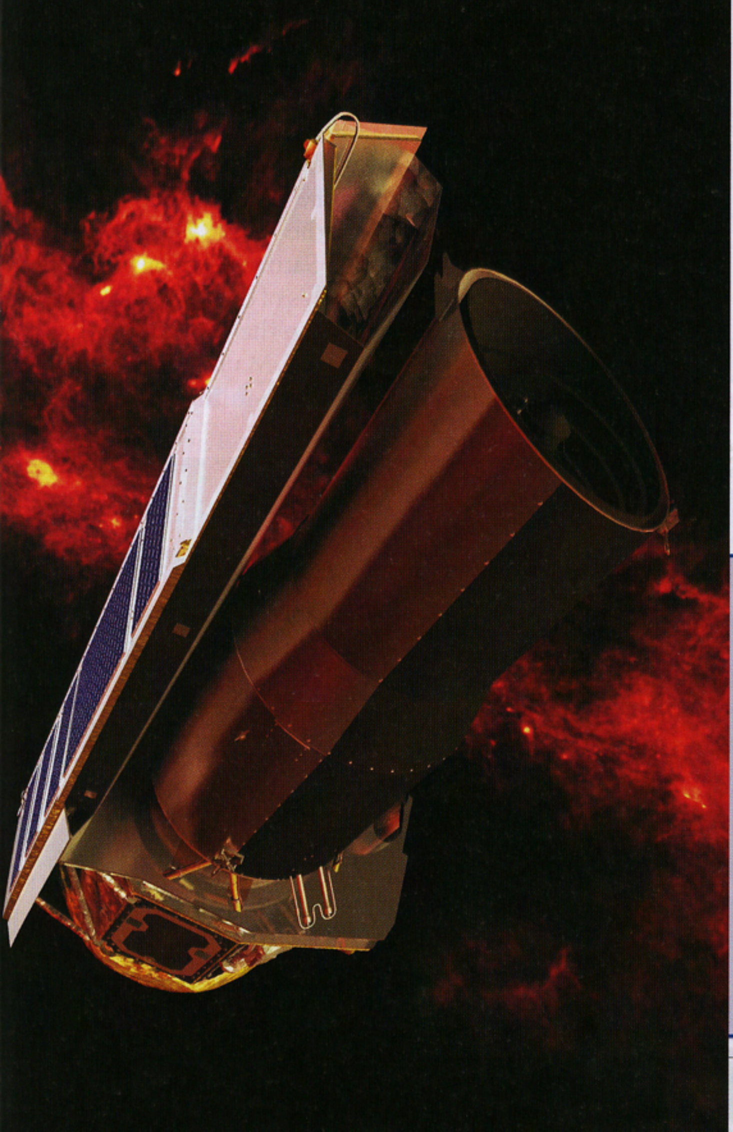
Debris Disk Sleuth: *The Spitzer Space Telescope*

Although the IRAS catalog was the 'mother lode' for debris disk studies, radio telescopes operating at sub-millimeter wavelengths, the Infrared Space Observatory and the Hubble Space Telescope (HST) have all played a role in discovery and exploration. Since 2003, NASA's infrared Spitzer Space Telescope has surveyed hundreds of stars with unprecedented sensitivity. Like IRAS, Spitzer is effective at detecting warm dust heated by the luminous A-type stars – about one quarter now have detections – but Spitzer is for the first time able to find debris disks orbiting solar-type stars. For stars older than a billion years, cold Kuiper belt-like disks are not uncommon, but warm asteroidal belt dust still eludes detection.

Princeton astronomer Amaya Moro-Martin has been using Spitzer to study the inconspicuous 6th magnitude star HD 38529. She has shown that this system provides a remarkable example of the relationship between debris disks and planetary systems. HD 38529 is a several billion-year old G-type star 42 parsecs from the Sun. This is the only known dusty, mature twin planet system. HD 38529 hosts two eccentric planets: a close-in 0.8 Jupiter-mass planet at 0.13 AU and a 12 Jupiter-mass planet at 3.7 AU. In this case the dust is cold and likely arises from a broad belt ten times more distant from the parent star than its outermost planet.

Another striking Spitzer discovery is the intense, asteroidal-belt emission from the nearby red (K-type) dwarf, HD 69830, which hosts three Neptune-mass planets with short orbital periods that place them all within 0.63 AU. The dust emission from HD 69830 is one thousand times more intense than that from of our own zodiacal cloud and exhibits the infrared fingerprint of small, crystalline silicate grains located within 1 AU of the star. Intense asteroidal belt emission is rare (less than 2 percent) leading to speculation that this dust cannot be persistent, but is likely the consequence of the recent catastrophic disruption of an asteroid or large comet. Perhaps the giant impact that formed the Earth's Moon about four billion years ago produced a similar cloud of debris.



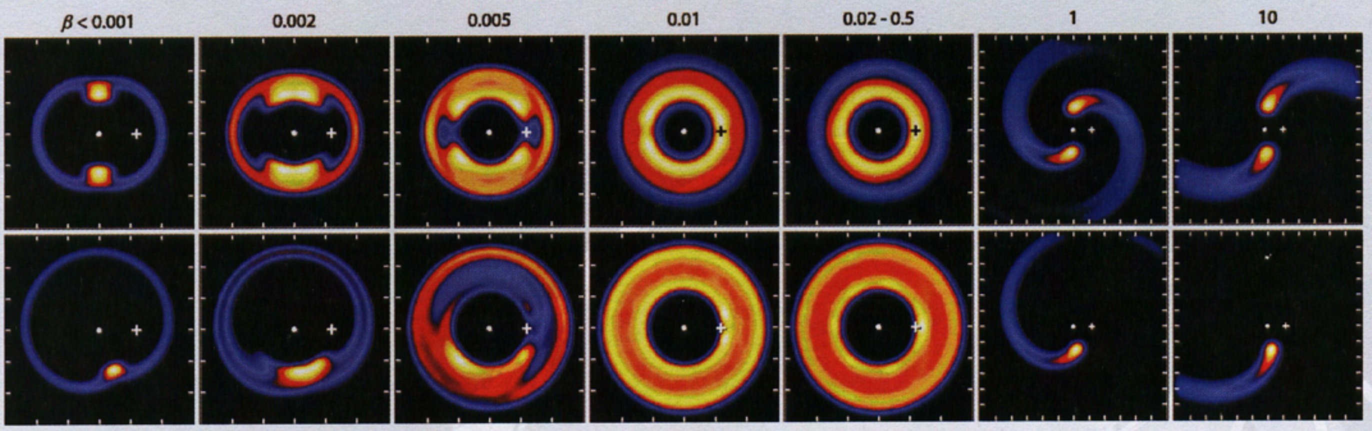


Debris Disks and Planets

Why should we care about debris disks now that extrasolar planets can be detected, and over two hundred are known? One important reason is that the principal exoplanet detection technique, the Doppler method, only works for billion-year-old stars, similar to the Sun, that have stable outer layers and are spinning relatively slowly. Not only that, the Doppler method is essentially sensitive to extrasolar giant planets in relatively close-in orbits, missing the smaller objects similar to Uranus or Neptune in mass and distance from the star. The inner edges of debris disks, on the other hand, are sensitive to gravitational perturbations from anything that is like an extrasolar Neptune.

■ ***Above:*** *AU Microscopii, the red dwarf star and sibling of Beta Pictoris, has a debris disk that was first imaged in 2004. These recent Hubble pictures show that the system resembles an edge-on view of Saturn's rings. The dark circle corresponds to the coronagraph spot that blots out the light from the star. The lower panel shows the polarized light signature, revealing the fluffy or porous structure of the dust present in this system. Image courtesy James R. Graham, Paul G. Kalas, and Brenda Matthews, STScI/ESA/NASA.*

■ ***Left:*** *An artist's impression of the debris disk sleuth extraordinaire the NASA/Spitzer Space Telescope. This observatory is sensitive to the infrared wavelengths of 3 to 180 microns radiated by circumstellar dust grains. The observatory was launched from Cape Canaveral, Florida on 25 August 2003. The 85-cm telescope is cooled to below 6 degrees above absolute zero by 360 liters of liquid helium. Image courtesy NASA/JPL-Caltech.*

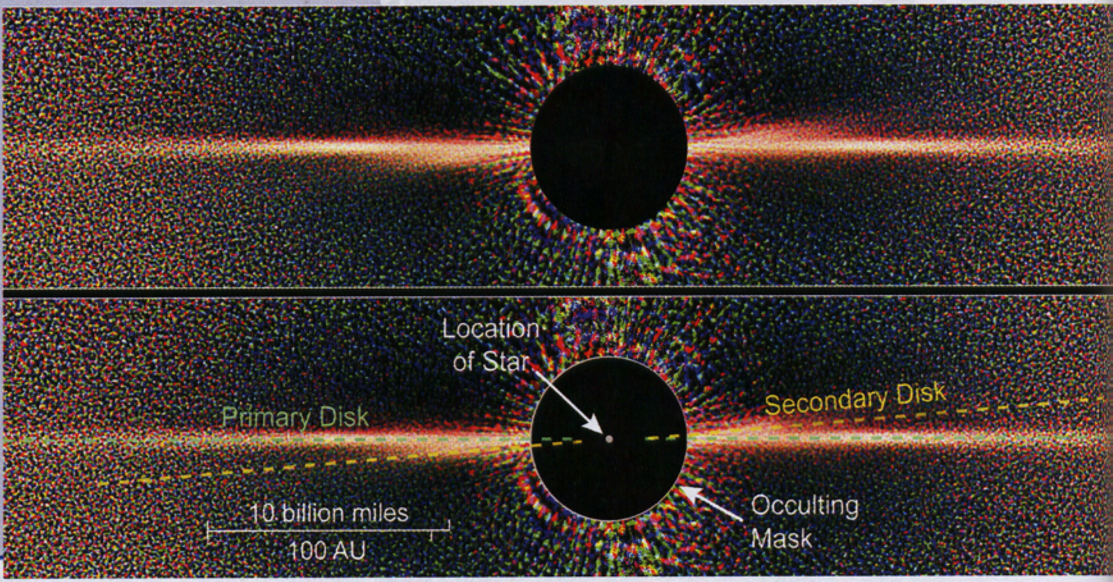


Over forty years ago, Tommy Gold, famous for developing the theory of steady state cosmology with Hermann Bondi and Fred Hoyle, realized that dust grains in our Solar System are likely to be driven into orbits that resonate with planetary orbits. If the gravitational pull of a planet like Jupiter were the only factor, then grains would be scattered out of the Solar System. In the 1950s Jan Oort and Gerard Kuiper envisioned that scattering by Jupiter and Neptune would populate the outermost regions of our Solar System with comets. This would also happen to dust grains, except that they are so tiny their motion is buffered by collisions with gas atoms, and their dynamics are further influenced by the scattering and absorption of sunlight. When combined with gravitational perturbations of planet, this portfolio of forces provides the dissipation necessary to concentrate matter into special orbits.

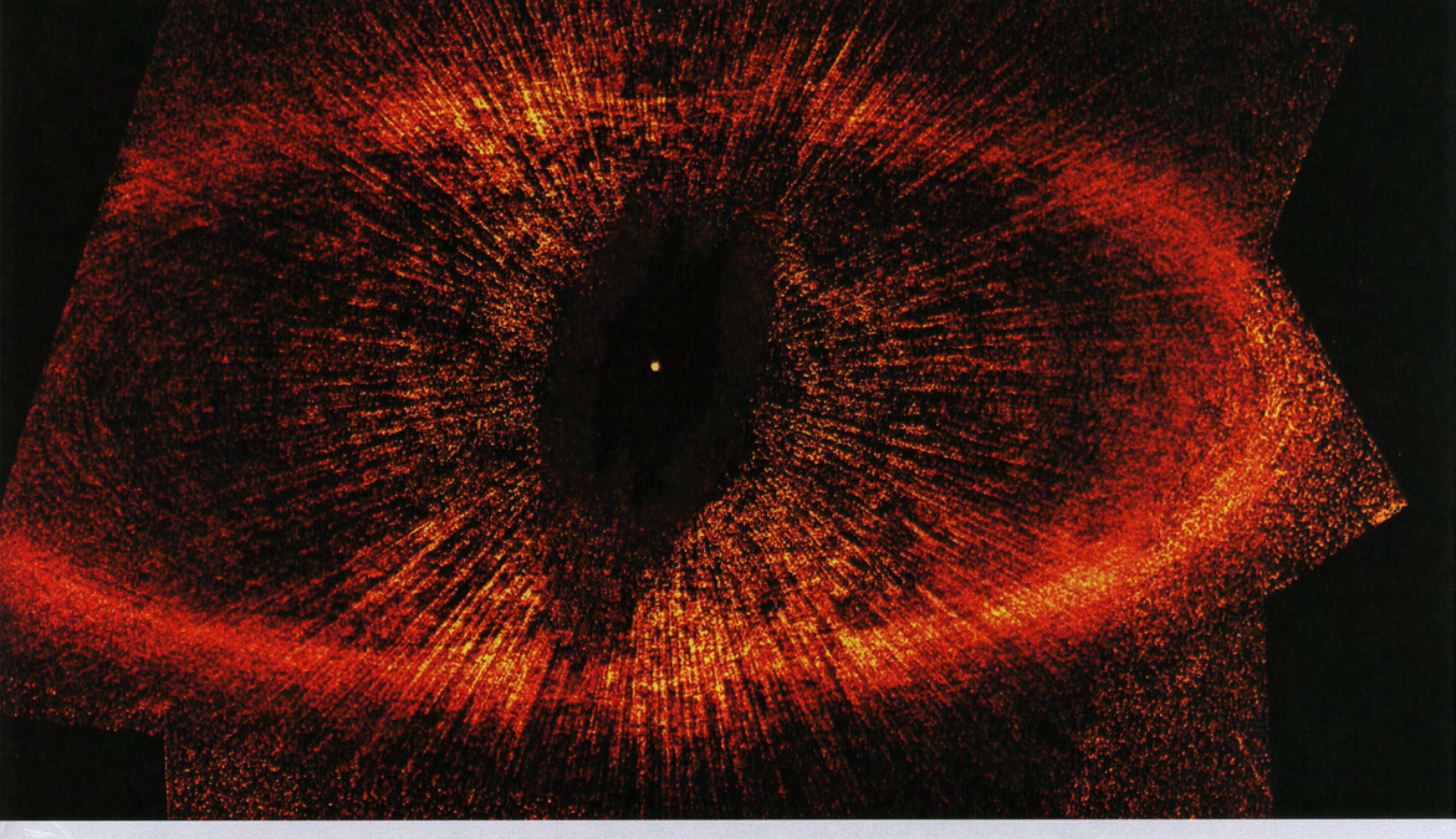
The relative importance of these forces depends on the size of grains, which means that grains are sorted according to how big they are. The largest grains have the same clumpy resonant distribution as comets and asteroids; moderate-sized grains are no longer in resonance and have an axi-symmetric distribution; and small grains are blown out of the system by radiation pressure and so have a density distribution that falls off inversely with distance from the star. As different wavebands – optical, infrared, and millimeter – are each sensitive to different dust grain sizes, a debris disk may have a very different appearance depending on the wavelength of light to which a camera is sensitive.

For example, take Vega's debris disk, where the entire system is thought to be oriented face-on from our point of view. If the Vega system were similar to the ringed planet Saturn, then our view is from the poles, and the rings of dust would neatly circle the star. Instead, when the 15-meter James Clerk Maxwell Telescope on Mauna Kea, Hawaii targeted Vega with its sub-millimeter

***Above:** Computer models of dust grains orbiting an A-type star. Each panel shows the distribution of dust grains of different sizes: smallest grains are on the right; largest on the left. The grains are created in the collisional destruction of planetesimals trapped in the 3:2 resonance with a massive planet that migrated outward from 45 AU to 60 AU. The color scale represents the abundance of dust. The smallest grains (two panels on the right) feel the effects of radiation pressure and fly out of the system on hyperbolic orbits. The planet's location is shown with a white plus sign, and its orbital motion is counterclockwise. Image courtesy M.C. Wyatt, Royal Observatory Edinburgh, copyright The Astrophysical Journal, 639: 1153-1165, 2006 March 10.*



***Right:** Two disks for the price of one! Very recent observations of Beta Pictoris with the Hubble Space Telescope show that a second disk lies hidden within the main disk. An occulting mask blots out the direct light from the star. Image courtesy D. Golimowski and NASA/ Space Telescope Science Institute.*



camera called SCUBA, the dust thermal emission was only found in one area 60 AU to the northeast of the star. Similarly, no neat circle of dust emission was found for Epsilon Eridani's dust disk – just a few clumps that if connected would form a ring 60 AU in radius. Fortunately, there is a very plausible explanation, which is that a yet undetected planet-mass object perturbs the dust into the resonances. Depending on the type of resonance (fundamental or harmonic), a star may have one or more concentrations of dust in its debris disk.

More Clues

For the Beta Pictoris and Fomalhaut debris disks it's not clumps that give away the presence of planets, but even more exotic features. Super-sensitive optical images of both stars using the Advanced Camera for Surveys aboard HST revealed that Beta Pictoris has a double disk, and that Fomalhaut is not a disk at all, but a narrow belt whose center is not at the position of the star, but 15 AU away from the star. The main Beta Pictoris disk, which has been studied in several hundred scientific papers over the past 25 years, is accompanied by faint sliver of light oriented a few degrees away from the main disk. Several theorists have proposed that an inner planet has an orbital plane that does not align with the main disk plane. The planet perturbs a belt of asteroids or comets vertically away from the main disk mid-plane, and dust from these primitive bodies then gets shot out to greater distances, explaining this surprising phenomenon.

Fomalhaut, the bright southern star visible to the naked eye beginning in the late summer, has a beautiful ring of material inclined about 30 degrees from edge-on. If you trace the outline of the belt and find its geometric center, you would miss the star by 15 AU. At first glance the reader may recall Kepler's Laws of planetary motion, which state that orbits are elliptical, and that the star is found at the focus, not the center, of the ellipse. This is true for a single orbit, but if you have billions of orbits for a population of comets, the ensemble would appear as a circular ring centered on the star. It was only recently that theorists Mark Wyatt and Stan Dermott showed that if a planet has an eccentric orbit around the star, then it could align the periastra of all the other bodies next to it such that the ring of comets shifts its center away from the star. Thus, when we look at the offset of Fomalhaut's ring relative to the position of the star, we are witnessing the effect of an unseen planet whose orbit around Fomalhaut is not perfectly circular.

■ ***Above:*** *The most detailed visible-light image ever taken of a narrow, dusty ring around the nearby star Fomalhaut offers the strongest evidence yet that an unruly and unseen planet may be gravitationally tugging on the ring. The light from Fomalhaut itself is hidden behind an occulting spot in the camera. The radial spokes are image artifacts due to imperfections in the mirrors of the Hubble Space Telescope. Image courtesy Paul Kalas, James R. Graham, and Mark Clampin, NASA/Space Telescope Science Institute.*

Exotica

Frank Shu, the famous Berkeley astronomer and co-inventor of the density wave theory of spiral galaxies, once quipped that there were only two types of astronomical objects: spheres and disks. Astronomers have known about the spheres – stars and planets – for millennia. Only recently has it become apparent how common and important disks are. Ordinary stars are orbited by gas and dust at various stages of their formation and evolution, but even in their final configurations as white dwarfs and neutron stars do disks occur.

In the 1990s UCLA astronomers Ben Zuckerman and Eric Becklin were searching for brown dwarfs orbiting white dwarfs when they discovered that the white dwarf G 29-38 had an infrared excess emission. They attributed this anomaly to a cool stellar companion. One of us (JRG) showed that the emission was due to dust orbiting in an asteroidal belt close to the star. This model has stood the test of time and additional white dwarfs with debris disks, such as GD 362, have been discovered in the past few years. In 2006, Boris Gaensicke (University of Warwick, England) and colleagues showed that a disk of calcium vapor orbits the white dwarf SDSS 1228+1040, making a stunning confirmation of the white dwarf/disk picture. The characteristic double-horned Doppler signature of the spectral lines of ionized calcium means that the outer edge of the disk extends to only 1.2 solar radii. The likely origin of the disk is a tidally disrupted asteroid, which had been perturbed from its initial orbit by a relatively massive planetesimal object or even a fully-fledged planet.

It is often argued that the first extrasolar planets were found in 1992 orbiting the spinning, magnetized neutron star PSR B1257+12 using the 300-meter Arecibo radio telescope. These earth-mass 'pulsar planets' must have formed from the debris of the supernova explosion that formed the neutron star. The fact that the pulsar planets orbit in a single plane suggests that they condensed out of a disk. In 2006, Spitzer observed that a different pulsar 4U 0142+61 appears to be orbited by about ten earth masses of debris in a disk.

■ ***Opposite page:** Successful testing of two of the 12-meter telescopes for Atacama Large Millimeter Array at the Very Large Array in New Mexico took place in March 2007. Eventually about fifty telescopes will work together on the Chajnantor plain of the Chilean Andes, 5000 meters above sea level to form the world's most sensitive millimeter observatory. Image courtesy Drew Medlin, NRAO/AUI/NSF.*

The Future

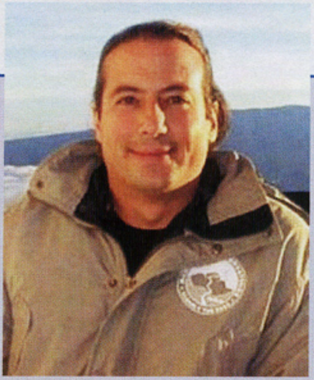
While some facilities such as HST and Spitzer are approaching the end of their missions, other powerful new observatories are coming on line. The prime camera on Hubble for imaging debris disks – the Advanced Camera for Surveys – suffered a fatal short circuit on 27 January 2007. Spitzer's days are numbered as its cryogenic helium is slated to run out in April 2009.

Just about every large, ground-based observatory is planning major upgrades that will produce the sharpest possible images using adaptive optics, and suppress the light from disk candidate stars using coronagraphs and other innovative techniques. Before the end of the decade both the European Very Large Telescope (SPHERE) and the Gemini Observatory's planet imager (GPI) will deploy powerful adaptive optics systems that will see faint debris disks and their planets.

The Herschel spacecraft will launch in 2008, in a dual configuration with the European Space Agency's cosmic microwave background mission, Planck. The Herschel is equipped with a 3.5-meter telescope, which dwarfs the 85-cm Spitzer primary mirror. The instruments aboard Herschel will provide superb resolution at wavelengths as long as 200 μm and be complementary to the long anticipated SCUBA-II camera for the James Clerk Maxwell telescope.

In the high Atacama Desert of northern Chile a revolutionary new astronomical facility is taking shape on the Chajnantor plain of the Chilean Andes, 5000 meters above sea level. The Atacama Large Millimeter/submillimeter Array (ALMA) will be a radio interferometer, like the Very Large Array in New Mexico, comprising about 50 individual radio dishes. ALMA will be able to detect dust masses as small as one percent of the mass of the Moon and at the highest frequencies will achieve a factor of ten better angular resolution than the Hubble Space Telescope.

The 6.5-meter diameter James Webb Space Telescope, which is expected to launch in 2013, will have three times the resolution of HST and a suite of infrared instruments capable of imaging new debris disks with unprecedented sensitivity. If the last few years provide any guide, be prepared for more surprises about planets and planet formation as these unique new observatories uncover the remarkable world of debris disks!



James R. Graham is a professor of astronomy at the University of California, Berkeley, where he is project scientist for the Gemini Planet Imager project - an "extreme" adaptive optics system designed to allow direct detection of exoplanets. Previously, Graham was a senior research fellow at the California Institute of Technology, Pasadena. His PhD is from Imperial College, University of London.

Paul Kalas is an observational astronomer at the University of California at Berkeley. His research programs focus on high-contrast, high-resolution imaging of dusty disks around nearby stars. He has utilized some of the world's largest telescopes, and among his accomplishments are the optical discoveries of debris belts surrounding the nearby stars Fomalhaut and AU Microscopii using the Hubble Space Telescope. Kalas' coronagraphic observations of nearby stars represent the largest database of its kind.