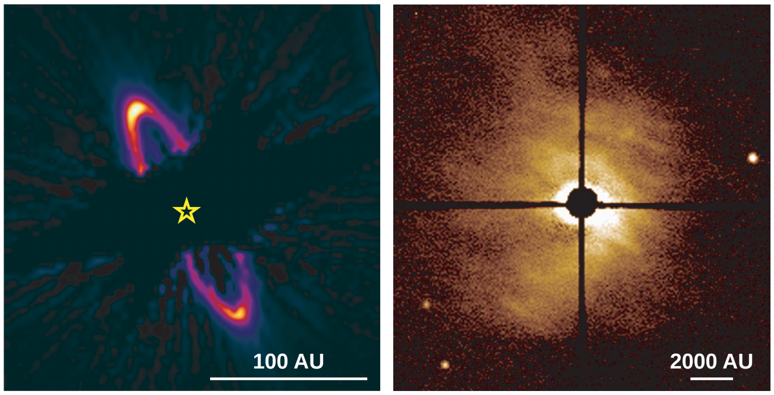
PERSPECTIVES: PLANETARY DISKS

A Dusty Business

Alycia J. Weinberger

In 1984, astronomers calibrating the data collected by the Infrared Astronomical Satellite (IRAS) discovered dust around the nearby star Vega (*1*). The study initiated a hunt for Vega-like stars—main-sequence stars surrounded by dusty disks that could provide insights into planet formation. Soon after, the first image of an exosolar system of planetary debris was recorded, showing a flattened disk of dust around the star β Pictoris (*2*). Recent studies are shedding light on the structure of these disks and the possible presence of planets.

The telltale sign of dust around Vega, β Pic, and other main-sequence stars was "excess" infrared (12 to 100 μm) emission above the level expected from the stellar photosphere. Excess emission is generated when dust particles around a star absorb ultraviolet and visible photons, heat up, and radiate their energy at longer wavelengths. In the solar system, such radiating grains exist in the form of the interplanetary dust particles (IDPs), generated when asteroids collide or comets sublimate. The dust grains are removed sufficiently quickly, so that their presence around main-sequence stars, as in our solar system, indicates that they are continuously replenished, hence the term "debris."



Disk or no disk? (Left) HST image of the disk around HR 4796A, an 8-million-year-old star 67 parsecs from the Sun (*9*). A narrow ring of dust 70 AU from the star may be confined by unseen larger bodies. The dust grains should be driven away from the system very quickly by the radiation pressure of the luminous central star. A reservoir of larger bodies must therefore be present to collide and produce this "debris." A coronagraphic wedge blocks the star and inner part of the disk. The instrumentally scattered and diffracted stellar light has been removed. **(Right)** Ground-based telescope image of the material around HD 23680, a main-sequence star 180 pc from the Sun (*3*). The nebulosity is not disklike but filamentary, suggesting that the star is traveling through a clump of interstellar material. The star is hidden behind a black disk supported by thin wires to keep its light from hitting the detector.

CREDIT: RIGHT PANEL ADAPTED FROM (3)/REPRODUCED WITH PERMISSION OF THE AMERICAN ASTRONOMICAL SOCIETY

The IRAS survey was the only all-sky survey at mid- to far-infrared wavelengths and took place almost 20 years ago. Since then, researchers have combed the IRAS catalog to find all sources with infrared excess. The problem with this approach is twofold.

First, the IRAS catalog is more sensitive to dust around luminous stars. The more luminous a star, the more stellar radiation will be intercepted—and therefore the more infrared radiation will be emitted—by dust in a given geometry. The IRAS mission disk census for Sun-like stars was therefore complete only to ~49 light years or ~15 parsecs (pc) from the Sun.

Second, as recently highlighted by Kalas and co-workers (*3*), stars have peculiar velocities, which can take them into clumps of interstellar material. When the star heats the surrounding dust, it can produce the same excess as a star heating its own debris disk. In images, however, the dust appears in large, unstructured, filamentary clouds unlike disks (see the figure, right panel). Kalas *et al.* found that 50% of currently identified excess stars may be of this type. However, the region of space near the Sun is relatively devoid of material, so this "Pleiades phenomenon" of fake Vega sources generally occurs further away, at more than 150 pc, than the disks that have been imaged around β Pic and other stars.

Imaging is thus important for confirming the disklike nature of circumstellar material. Furthermore, it can reveal structure in the disks. In our solar system, material is distributed nonuniformly as a result of perturbation by our planets. Small planets in other systems may betray themselves by such perturbations of their stars' disks, even if they do not lend themselves to detection via currently available means such as radial velocity surveys.

In the last decade, many new large ground-based telescopes have been outfitted with sensitive infrared arrays. Although state-of-the-art mid-infrared arrays still have fewer than 10^5 pixels compared with the 10^7 pixels of their optical counterparts, they are an order of magnitude more sensitive than IRAS was at wavelengths of 10 to 20 μm. At shorter (visible to near-infrared) wavelengths, the sensitivity and high angular resolution of the Hubble Space Telescope (HST) can be exploited.

With these tools, the distribution of grains in the disks can now be studied at a scale approaching that of the inner solar system. Thermal emission (at mid-infrared to millimeter wavelengths) provides information on grain sizes and compositions, and scattered-light imaging (in the visual to near-infrared) gives temperature-insensitive measures of the disk structure with high spatial resolution to large distances from the central star. The combination of infrared emitted and visual scattered-light measurements allows a determination of the albedo of the grains.

However, imaging is very challenging. To date, combined emission and light-scattering measurements exist for only a few disks, yielding albedos of 0.2 to 0.5 (*4*). This is fairly high compared to the outermost residents of our own solar system, the Kuiper Belt Objects, which typically have albedos of less than 0.1, and is more in the range expected for dirty ices. Fewer than 10% of all known Vega-like disks have been spatially resolved at any wavelength.

Recent millimeter-wave interferometric images of Vega by two groups (*5*, *6*) show that the cold grains around the star are not uniformly distributed in a smooth disk. Clumps of material at 90 AU (1 AU = 15 × 10^7 km) from the star may be a result of resonant interactions with an unseen planet. A smooth underlying dusty ring may still be present, but attempts to detect scattered light from the dust have heretofore been unsuccessful. Vega is extremely close to us but has a very weak infrared excess (0.002% stellar luminosity) and is viewed nearly pole-on, so the scattered light likely has low surface brightness.

Evidence of asymmetric structures and clumpiness is also emerging from scat-

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The author is in the Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA. E-mail: weinberger@dtm.ciw.edu

tered-light imaging of other disks. The disk of β Pic is viewed nearly edge-on, extending like a thin ribbon of light from within 5 AU to more than 1000 AU from the star. The data indicate that at least three different regions of the disk are tilted or warped with respect to each other (*7*). The perturbation of material in this way has been modeled successfully under the assumption that a giant planet orbits within it (*8*).

Around HR 4796A, a star with slightly more infrared excess than β Pic, dust is largely confined to a narrow ring of material 70 AU from the star (see the figure, left panel) (*9*). One endpoint of the ring is brighter than the other, suggesting a clumpy distribution of dust along the ring. In our solar system, Saturn's narrow rings are shepherded dynamically by its moons, and it is tempting to invoke the effects of planets in the HR 4796A system as a dust-confining mechanism.

The disks imaged to date form a heterogeneous group, with little in common in terms of structure even when the central stars are quite similar. All are considerably larger than our known solar system, raising the question of whether they (or we) are typical.

But many more excess stars may soon be found by targeted observations. In the last few years, a large number of fairly young stars (ages of <50 million years) has been identified close to the Sun (<100 pc) (*10*). Young stars generally have more dust, and close stars can be studied with the best spatial resolution, so these stars should be a boon to disk studies both from the ground and from space. NASA's next great observatory, the Space InfraRed Telescope Facility set to launch in January 2003, will search for dust at solar system levels around 300 stars with a wide range of ages, including mature stars like the Sun.

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PERSPECTIVES: PALEONTOLOGY

East of Eden at the Paleocene/Eocene Boundary

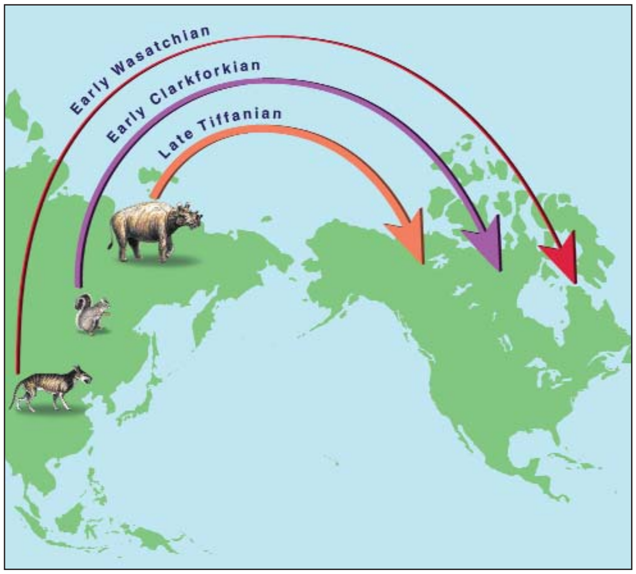
Chris Beard

Geologists divide the long saga of Earth history into chapters known as eras, periods, and epochs. Even before Darwin published *Origin of Species*, these intervals were recognized on the basis of the distinctive fossil assemblages that characterize them. Understanding how, when, and why these ancient ecosystems replaced one another remains a central question for both the earth and life sciences.

On page 2062 of this issue, Bowen *et al.* (*1*) present data bearing on the most dramatic biotic change of the last 65 million years (the Cenozoic Era), popularly known as the "Age of Mammals." This radical reshuffling of Earth's biota coincided with a brief but intense episode of global warming at the Paleocene/Eocene (P/E) boundary, about 55 million years ago (*2*).

The climatic perturbation was fleeting, but its biological effects were permanent. Across the Northern Hemisphere, a wave of anatomically modern groups of mammals appeared in the Eocene, at the expense of archaic forms that became extinct (*3*). Other major components of the ecosystem changed at the same time (*4*). Given the brevity of the P/E boundary events, how did such a rapid overhaul of terrestrial ecosystems occur?

The pattern of biotic change at the P/E boundary is documented best in the Bighorn Basin of Wyoming, USA, where a nearly continuous sequence of fossiliferous rock strata provides a uniquely detailed window on mammalian turnover across the P/E boundary. The Bighorn Basin record shows that the mammalian fauna changed abruptly at the P/E boundary, when the earliest North American primates, artiodactyls, perissodactyls, and opossum-like marsupials (Didelphidae) show up en masse (*5*). This cohort of modern mammals was accompanied by other groups, such as the carnivorous Hyaenodontidae and the enigmatic Hapalodectidae, that later fell prey to extinction.



East of Eden. Phylogenetic data suggest that Asia was the geographic source for many mammalian groups that later spread to Europe and North America. The fossil record implies that Asian mammals invaded North America at least three times near the P/E boundary. The three waves of Asian mammals included uintatheres (order Dinocerata), which dispersed to North America 57 million years ago (Late Tiffanian); rodents, which first appeared in North America 56.3 million years ago (Early Clarkforkian), and hyaenodontids, which migrated to North America 55 million years ago at the P/E boundary (or Early Wasatchian). New geochronological evidence from China supports this iterative biogeographic model.

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Each new type of mammal marking the beginning of the Eocene already sports the characteristic anatomy that defines its group. The newcomers differ so fundamentally from North American Paleocene mammals that they could not have evolved in situ. A similar pattern of biotic change occurred in western Europe, although the fossil record is less densely sampled there (*6*).

Faunal turnover across the putative P/E boundary in Asia differs from that observed in North America and Europe. In Asia, the carnivorous Hyaenodontidae and the odd-toed Perissodactyla (horses, rhinos, and tapirs) are recorded from fossil sites assigned to the Gashatan

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The author is in the Section of Vertebrate Paleontology, Carnegie Museum of Natural History, Pittsburgh, PA 15213, USA. E-mail: beardc@carnegiemuseums.org