

Infrared evidence for protoplanetary rings around seven stars

For the lonely among us who are eager to make contact with life elsewhere in the Universe, the abundance or scarcity of planetary systems around other stars is a particularly interesting question. Tentative reports of gravitational perturbations in the positions of a few nearby stars have been taken as very inconclusive evidence of planets, but until last summer we had no direct evidence of solid, non-stellar material orbiting any star other than our own.

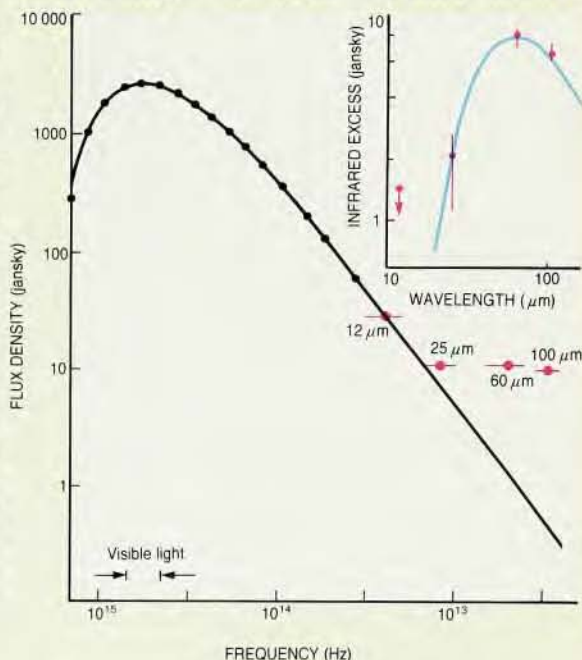
Since the first reports, last summer, that the Infrared Astronomy Satellite (IRAS) had discovered a shell, or disk, of small particles apparently orbiting Vega at a distance of about 85 astronomical units (roughly twice the orbital radius of Pluto), infrared telescopes have detected similar, presumably "protoplanetary," systems around six other stars in our neighborhood.

IRAS was launched into a 560-mile-high polar orbit in January 1983. Before it ran out of its superfluid-helium coolant ten months later, this orbiting 23-inch infrared telescope had expanded the catalog of known infrared sources in the Cosmos from a few thousand to about a quarter of a million. Last December, four months after the Vega announcement, the IRAS team reported the discovery of a similar protoplanetary system around Fomalhaut, another nearby star prominent in the summer night sky. IRAS is a joint undertaking of the US, UK and the Netherlands. These circumstellar systems, of course, represent only a small part of the cornucopia of unique findings IRAS has made available to us.

At a conference on protostars and protoplanets, held in Tucson last January, it became clear that ground-based infrared telescopes had begun to encroach on the IRAS monopoly. A Cornell-UCLA-University of Hawaii group reported that their infrared observations with the 4-meter Kitt Peak telescope and two infrared telescopes on Mauna Kea had indicated the presence of disks of small particles orbiting HL Tauri and R Monocerotis, two obscure stars much younger and further away than Vega and Fomalhaut. At the same meeting, a collabora-

IRAS measurements (color) of infrared radiation from Vega at 25, 60 and 100 microns lie well above the tail of the blackbody radiation (black curve) expected from this 9700-K star.

Only the 12-micron IRAS measurement fits the stellar curve, as do the ground-based measurements (black dots) at shorter wavelengths. Subtracting the stellar blackbody tail from the IRAS data (inset), one finds that the infrared excess fits an 85-K blackbody curve (color), suggesting a ring of small particles orbiting the star at a distance of 85 AU. This agrees with the IRAS measurement of the spatial extension of the infrared Vega source.



tion from the Universities of Massachusetts, Wyoming and Hawaii presented preliminary independent data from the 3-meter Infrared Telescope Facility on Mauna Kea supporting the existence of the HL Tau disk, and the IRAS group reported evidence for protoplanetary disks around ϵ Eridani and β Pictoris, two rather faint nearby stars. Since the Tucson conference, the Massachusetts-Wyoming-Hawaii group has seen what appears to be a particulate disk around Lynds 1551/IRS 5, a very young star visible only in the infrared because its visible radiation is obscured by the dark molecular cloud (Lynds 1551) that gave it birth.

Satellite vs. ground-based infrared. With its four sets of infrared detectors looking at wavelength bands around 12, 25, 60 and 100 microns, IRAS appears to be seeing primarily thermal radiation from the particles in these circumstellar disks, warmed to temperatures on the order of 50 to 100 K by the radiation from their stars. At 85 K, the estimated temperature of the Vega

disk, for example, the blackbody spectrum peaks at 60 microns. The ground-based telescopes, by contrast, are looking at shorter infrared wavelengths—on the order of 2 to 4 microns—presumed to be starlight scattered, rather than thermally reradiated, by the circumstellar particles.

With larger apertures looking at smaller wavelengths, the diffraction limits of the groundbased telescopes—typically a tenth of an arcsecond—are almost 2 orders of magnitude better than that of IRAS. But on the ground one has to contend with atmospheric turbulence, which even at favored sites such as Hawaii's 14 000-foot Mauna Kea, blurs "seeing" to about one arcsecond at the best of times. Both ground-based groups have, however, exploited tricks to improve their resolutions well below this seeing limit.

Ground-based infrared observations are also limited by atmospheric absorption to a few "windows" in the spectrum. At wavelengths longer than 22 microns, absorption by atmospheric

microns, absorption by atmospheric water vapor renders ground-based observation all but impossible. But even in the relatively clear windows just below 22 microns, telescopes at earth-surface temperature have to contend with a thermal background that makes it very difficult to see the thermal radiation from cool sources such as these circumstellar disks. The ground-based groups therefore prefer to observe *scattered* starlight at much shorter infrared wavelengths, where the ambient thermal background is minimal.

With its more limited angular resolution, the IRAS team has concentrated its search for protoplanetary systems on stars in our immediate neighborhood. Vega and Fomalhaut are both only about 8 parsecs (25 light-years) away. At a distance of only 3 pc, ϵ Eri is our eleventh nearest stellar neighbor. The extended Vega infrared source subtends an angle of more than 20 arcsec, easily resolvable by IRAS. Beyond 25 pc, the distance limit the group has set for its present search, IRAS would have difficulty identifying an extended source a few hundred AU wide. "In any case," says Hartmut Aumann of the IRAS team, "if there's anybody out there, I'd sure like them to be close by."

Availing itself of speckle interferometry, the Cornell-UCLA-Hawaii collaboration can, in principle, get down to a diffraction-limited resolution of 0.1". The group has therefore chosen to look at very young stars much further out. HL Tau is about twenty times farther away than Vega and Fomalhaut, a distance at which a typical protoplanetary disk would subtend an angle of little more than an arcsecond. Although Vega, Fomalhaut and β Pic are A-class stars only about a tenth as old as our 5 billion-year-old Sun, Steven Beckwith (Cornell) points out that they are probably too old still to be at the stage of incipient planetary formation, which, it is generally believed, takes place on a time scale of only a few million years. HL Tau, R Mon and Lynds 1551/IRS5 are less than a million years old, having not yet reached the main-sequence stage of stellar maturity. He suggests that in these circumstellar systems we are probably seeing early stages of planetary formation, whereas the Vega and Fomalhaut systems are more likely to be left-over debris accompanying planets already formed. (Fully formed planets, as distinguished from disks or shells of small particles, are not detectable by these infrared telescopes, because of their much lower surface-to-volume ratio. The brightness of the infrared signal is of course proportional to the effective surface area of the source.) To find the relatively rare stars young enough still

to be in the process of planet formation one has to look farther afield, to distances where resolving power becomes a crucial issue. Thus Beckwith regards the ground-based and IRAS observations as complementary approaches, each elucidating a different stage in the history of planetary systems.

The Vega discovery.¹ In the spring of 1983, was quite serendipitous. Because Vega is one of the brightest stars in the northern sky, it was to serve as a calibration object for IRAS. Looking at the early calibration data from Vega telemetered to the IRAS data-acquisition station at the Rutherford Laboratory in England, Aumann (from JPL) and Fred Gillett (from Kitt Peak) at first thought there must be an instrumentation problem. Vega appeared to be about ten times brighter at 60 microns than one would expect of such a star, with a surface temperature of 10 000 K. But none of the other calibration stars exhibited such an infrared anomaly. They therefore telemetrically ordered high-angular-resolution infrared scans of Vega in two orthogonal directions. IRAS executes such scans by sweeping the telescope across the object so that its narrow-slit image sweeps across the solid-state detectors in the focal plane. Filters in front of the detectors select the appropriate wavelength bands.

At 12 microns, Vega looked quite pointlike, as one expects for a stellar source. But at 60 microns, the source of the infrared emission appeared to be $23'' \pm 6''$ wide. In the orthogonal direction, the extended region of infrared emission appeared somewhat narrower, but the difference was not sufficiently pronounced, given the angular resolution, to say whether the extended infrared source is circular or elliptical. This is an important issue, because one would expect an orbiting protoplanetary system to be a flattened disk rather than a spherical shell. Seen from a random direction, such a disk would appear elliptical. A circular emission region could perhaps be argued away as a cloud of ejected or infalling material, much less exciting than an orbiting aggregate.

Whereas the brightness measurement at 12 microns fell nicely on the infrared tail of the emission spectrum one would expect of a 10 000 K star, the intensities measured at the longer wavelengths fit well to a blackbody spectrum at 85 K. This effective temperature measurement turns out to be in astonishingly good accord with the size measurement of the extended cool source. At the distance of Vega, the measured angular size corresponds to a region extending out about 85 AU from the star. Assuming a ring of particles 85 AU from Vega, with particle sizes of at least 20 microns, one calculates that such a ring would be warmed to just

about 85 K by radiation from the star. "The result was so surprisingly good," Aumann told us, "that we had to do the calculation a second time before we believed it." The absence of a warmer component in the excess infrared spectrum implies that very little of the material is much closer to the star than 85 AU. This suggests an annular disk with a large central hole, but the angular resolution of the telescope does not permit one to see this hole directly.

The brightness of the Vega's excess infrared spectrum suggests a thermally radiating source with an effective area about four thousand times that of the star itself. Although the spectrum and size of the extended source yields a lower particle-size limit of 20 microns, the group argues that if the ring has been in orbit around Vega since the star's formation, particles smaller than a millimeter would long since have spiraled into the star by the Poynting-Robertson radiation-drag effect. The IRAS data provide no upper size limit for the particles in the ring, but with a plausible assumption about the size distribution of longer particles the group concludes that the total mass of the ring is about 300 Earth masses, comparable to the mass of our own planetary system. There is no direct evidence from IRAS that what one is seeing is indeed an orbiting ring rather than an expanding shell of ejected material from the star. But Aumann points out that Vega has been under close scrutiny for centuries, showing itself to be a very stable star with no evidence of such mass ejection.

Having convinced themselves that the extended infrared source around Vega is real, the IRAS group undertook a systematic search that promptly turned up a similar system around Fomalhaut, the brightest star in the constellation Piscis Austrinus. Its excess infrared spectrum, as measured by IRAS, indicates a circumstellar ring somewhat cooler (65 K) than that surrounding Vega. But, once again, this spectral temperature is in good agreement with the equilibrium temperature calculated for the slightly larger radius measured for the Fomalhaut ring and the lower temperature of the star itself.

The Vega observation has since been confirmed by the Kuiper Airborne Observatory, a telescope-equipped jet operated by NASA. The analysis of the β Pic and ϵ Eri data is still incomplete, but β Pic seems to be providing good evidence of the presumed disk-like character of these sources. In one scan direction it looks 400 AU wide, while in the orthogonal direction it shows no width beyond the limit of IRAS resolution. The β Pic disk is not only more extensive than its fellows; it also appears to have a broader temperature

range, with warm regions quite close to the star radiating significantly at 10 microns. Because of its proximity and longevity, ϵ Eri has been the subject of much speculation as to its habitability. ϵ Eri is a slow-burning, cool, K-class star with a life expectancy three times that of the Sun.

Beckwith and his collaborators, Benjamin Zuckerman (UCLA), Michael Strutske (Cornell) and Melvin Dyck (Hawaii), believe they are seeing Rayleigh-scattered infrared starlight from HL Tau, scattered by a 320-AU-wide disk of dust grains no larger than a few tenths of a micron. (Strictly speaking, this would be Mie scattering.) Observing at infrared wavelengths of 2.2 and 3.8 microns, the group found that at 2.2 microns the extended scattering source was at least 20% as bright as the star itself. The much-reduced scattered intensity at 3.8 microns, characteristic of the steep falloff of Rayleigh scattering with increasing wavelength, yields the conclusion that the scattering particles are significantly smaller than the wavelength of the scattered light.

HL Tau is about 150 parsecs distant from us. With the good resolution afforded by speckle interferometry, the group was able to conclude that in the direction orthogonal to its 320-AU width the extended source was only 160 AU across, strongly suggesting a disk seen from Earth at a tilt. Speckle interferometry takes advantage of the fact that the atmospheric blurring of a celestial object is the consequence of a relatively long-term time averaging of an image distorted by the ever-changing turbulent atmosphere. With very short "snapshot" exposures one finds the image still distorted, but in a manner more frozen in time. One sees a collection of "speckles," bright interference maxima from different portions of the distorted wavefront impinging the telescope mirror that happen to reach the focal plane in phase. If the angular size of the source is smaller than the diffraction limit of the telescope, the smallest of these speckles—resulting from constructively interfering regions at the opposite extremes of the primary mirror—will have the size of the instrument's diffraction limit. If the source is resolvable—larger than this diffraction limit—the smallest speckles will have the angular size of the extended source. With visible light, one sees these speckles only with exposures shorter than about 20 milliseconds, but at infrared wavelengths, 200 msec is short enough.

The Cornell-UCLA-Hawaii group drives the telescope's secondary mirror in such a way as to sweep the stellar image rapidly across a narrow slit in the focal plane. The InSb detector behind the slit records the varying intensity during the 200 millisecond



Polarized infrared images of the star HL Tau, 150 parsecs distant. With the polarization axis normal to the direction of widest extension, the Massachusetts-Wyoming-Hawaii group sees (top) an asymmetrically extended source, suggesting a circumstellar dust ring more than 300 AU wide. Rotating the polarizer 90°, one sees (bottom) only an unresolved circular image. The squares are 12 arcseconds wide.

sweep—effectively a one-dimensional projection of the speckle pattern. This projection is digitally stored and Fourier transformed. About a hundred such sweeps are performed in rapid succession, followed by a series of sweeps of a nearby calibration star—a known infrared point source.

After noise subtraction, the absolute squares of these hundred successive Fourier transforms are averaged and compared with the corresponding average for the point source. By averaging absolute squares, one is throwing away the phase information from each Fourier transform. This is equivalent to superposing speckles while ignoring their absolute positions, which dance around from moment to moment. To determine the shape and angular size of the object, one examines the ratio of this averaged Fourier spectrum to that of the calibrating point source as a function of spatial frequency. By repeating the procedure in the orthogonal direction, one gets the other projec-

tion of the image.

With this speckle interferometric technique the group was able to resolve spatially the infrared light scattered off the disk from that coming directly from the star. The disk around R Mon was found by this method to have about the same angular size as that of HL Tau. But because it is four times as far away from us, one concludes that the R Mon disk is about 1000 AU across. From the absorption and emission features of the dust grains responsible for the observed scattering, the group suspects them to be primarily silicates. They estimate the total mass of such silicate grains in the HL Tau disk to be about one Earth mass, with the R Mon disk being five times as massive. From estimates of relative abundance, they conclude that the orbiting disks also contain a mass of gas hydrogen comparable to the mass of the Jovian planets. The scattering grains around these very young stars appear to be much smaller than those seen by IRAS. This probably indicates, Zuckerman told us, that around HL Tau and R Mon we are seeing a much earlier stage of planetary history.

The Massachusetts-Wyoming-Hawaii collaboration, also using the IRTF on Mauna Kea, discovered the HL Tau disk at about the same time as Beckwith and company. Their technique for circumventing the seeing limit on ground-based telescopes is complementary to speckle interferometry. Stephen Strom (University of Massachusetts) told us that the collaboration's "maximum-entropy image reconstruction" technique cannot achieve the diffraction-limited resolution attainable with speckle interferometry; it can only beat down the seeing limit by about a factor of 2. But it can be employed with much fainter sources, and it provides two-dimensional images directly rather than pairs of one-dimensional projections.

Strom and his colleagues, Karen Strom (Massachusetts), Gary Grasda-len and Michael Castela (Wyoming), and Richard Capps and DeAnne Thompson (Hawaii), observing HL Tau last fall and winter at wavelengths of 1.6 and 2.2 microns, came to essentially the same conclusions about the circumstellar disk as Beckwith's group. With an effective resolution of about half an arcsecond, however, they could not separate the starlight from the disk-scattered light as clearly as was possible with the speckle technique.

The maximum-entropy reconstruction procedure uses a deconvolution algorithm to reconstruct the smoothest possible image from heavily oversampled image data taken together with images of a nearby reference star under the same seeing conditions. The focal-plane image is digitized by passing it over the detector in a highly redundant

raster scan. That is to say, each pixel in the scan has a great deal of overlap with its neighbors. Each image scan is followed by a similar scan of the reference point-source star. The reconstruction algorithm is an iterative deconvolution calculation that uses the observed smearing of the known point source to extract the true image from its presumably identical smearing. A free parameter (effectively a Lagrange multiplier) is varied until the recovery of additional information from the image is maximized and any further recovered "information" begins to look unrealistic.

The sensitivity of this technique for faint sources lets the group exploit polarization information to strengthen the scattering-disk hypothesis. If the extended HL Tau source is indeed a disk of scattering dust particles, starlight scattered from its outer edges will be polarized perpendicular to the disk plane. Interposing a polarizer oriented in this direction, the group did indeed see the full, asymmetrically extended HL Tau image; but with the polarizer axis parallel to the apparent disk plane

the image was no longer resolvably extended.

Lynds 1551/IRS5 is a very faint infrared stellar source in the same Taurus molecular cloud complex in which HL Tau was born. Presumably because it is even younger than HL Tau, Lynds 1551/IRS5 has not yet extricated itself from the cloud sufficiently to be seen at visible wavelengths. The suspicion that IRS5 might have a circumstellar disk was raised by the fact that one sees a pair of very energetic jets bursting forth from the cloud, presumably resulting from highly collimated material ejected by the star. A circumstellar disk would serve as a mechanism for such a polar collimation of ejecta. The group has indeed now found evidence for an infrared scattering disk, about 500 AU wide, around this faint star, still imbedded in its womb.

—BMS

Reference

1. H. Aumann, F. Gillet, C. Beichman, T. de Jong, J. Houck, F. Low, G. Neugebauer, R. Walker, P. Wesselius, Ap. J. (Letters) 218, L23 (1984).

Orbiting gyro test of general relativity

Over twenty years have elapsed since Leonard Schiff at Stanford and, independently, George E. Pugh at the Defense Department predicted¹ that a gyroscope in orbit about Earth would precess as a consequence of Einstein's general theory of relativity. Such behavior depends on an aspect of the theory of gravity that remains untested to this day. Although the concept is simple, the experiment is formidable: The precession is about 44 milliarcsec/year, to be measured with an accuracy of 1 milliarc-sec per year. Undaunted, Schiff, together with Stanford colleagues William Fairbank and Robert Cannon, respectively, set up a program to develop the experiment. Since 1962, a Stanford team led by Francis Everitt and later having the support of NASA's Marshall Space Flight Center, has patiently and persistently toppled² many technical barriers, bringing the experiment from the realm of the improbable into the world of the possible. In late 1980, a committee of 16 scientists and engineers convened by NASA spent five days reviewing the technical readiness of the experiment, which is called the Gravity Probe B. They gave it a sound endorsement and concluded it was now ready to proceed to its flight phase.

Since then the Stanford team has endeavored to develop a satisfactory flight program. Eighteen months ago, NASA rejected as too expensive a \$200- to \$300-million plan that would have involved an elaborate, land-based engi-

neering development followed by the launch in 1992 of a very large (2400-kg) spacecraft. During the past year, the design has been greatly simplified. The proposal reduces the spacecraft weight to 1300 kg and sets forth a less costly plan to develop the high-technology portion of the experiment (the instrument assembly). The system would be tested aboard the Space Shuttle in three to four years, with this first phase costing \$50 million. The experiment would then proceed with a subsequent free flight in space if all systems worked during the shuttle flight.

Last fall, NASA unexplainedly delet-

ed funds for the Gravity Probe B from its FY 85 budget request. Several prominent physicists wrote to NASA in support of the experiment, and the Space Science Board responded directly to NASA's budget cut with a strong endorsement of the Gravity Probe B, stating that it "fully addresses [their] highest priority science objective in gravitational physics." Frank McDonald, chief scientist for NASA, told us that although NASA had not yet made a final decision on Gravity Probe B, NASA is optimistic about the prospect that it will go ahead with an engineering test on the Shuttle.

During the years of development of the Gravity Probe B, theoretical interest in the project has, if anything, intensified. Because the gyroscope can detect spin-sensitive aspects of the gravitational interaction to which other (easier) tests of relativity are insensitive, it may provide a qualitatively different test of Einstein's theory of general relativity—and a negative result is not necessarily unexpected. In his letter of endorsement to NASA, Chen Ning Yang (State University of New York, Stony Brook) felt he spoke for many theorists in asserting that Einstein's general theory of relativity, while profoundly beautiful, may need to be amended. One reflection of the inadequacy of the theory in its present form is the lack of success in attempts to quantize it. Yang believes that the correct, geometrically symmetric form of the theory will most likely involve spin and rotation.

Gyroscope precession. Schiff deduced that two effects would cause the precession of the gyroscope, corresponding to two terms in the following equation:

$$\Omega = \frac{3GM}{2c^2 R^3} (\mathbf{R} \times \mathbf{v}) + \frac{GI}{c^2 R^3} \left[\frac{3\mathbf{R}}{R^2} (\boldsymbol{\omega} \cdot \mathbf{R}) - \boldsymbol{\omega} \right]$$

where Ω is the precession rate, $\mathbf{R}$ and $\mathbf{v}$

Gravity Probe B would contain four gyroscopes mounted along the main axis of the satellite and contained within the helium dewar. Gas escaping from the dewar would drive the proportional thrusters to keep the satellite axis pointed towards a distant star. This free-flight version is the final step after the proposed test aboard the Space Shuttle.

