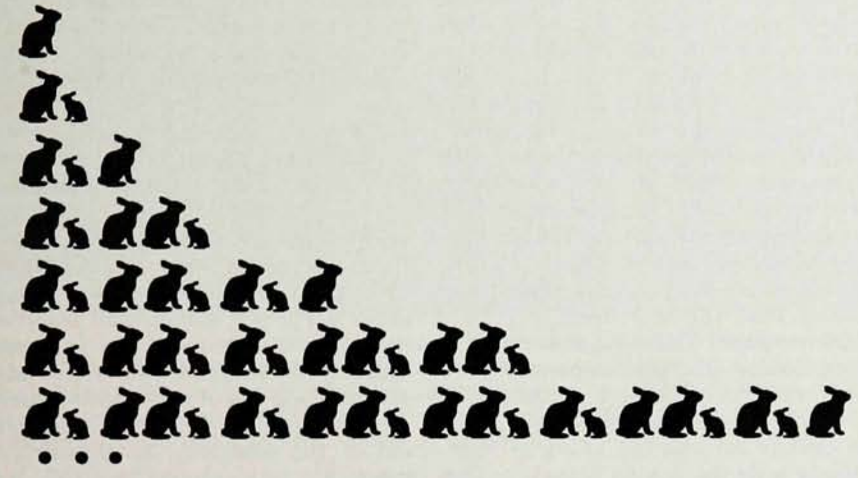
Quasiperiodic rabbit breeding

The Fibonacci sequence that determines the alternation of long and short spacings along a quasicrystal axis first arose when the medieval mathematician Leonardo Fibonacci of Pisa considered the idealized propagation of rabbits. If at the end of every year every adult rabbit produces one baby and every one-year-old baby becomes an adult, one sees the following evolution from year to year (assuming rabbits are immortal):



The sequence never becomes periodic. If "adult" and "baby" are regarded as spatial intervals whose ratio is 1.618 . . ., the golden mean, one has what Steinhardt calls a quasiperiodic sequence. With other generation rules one gets other quasiperiodic sequences having different length ratios, but the ratio must be an algebraic, irrational number.

is rigorously deterministic. He characterizes the Penrose patterns and their three-dimensional generalizations as "quasiperiodic" rather than aperiodic. The quasilattice points are generated by the intersections of families of parallel planes (or lines) whose consecutive spacings alternate between two characteristic lengths in a Fibonacci sequence (see box). It should come as no surprise that the ratio of the longer to the shorter spacing is the golden mean.

Thus, in the direction of each of the fivefold symmetry axes, one has a nonperiodic but quite deterministic alternation between two incommensurable lengths (the golden mean being an irrational number). Working out the Fourier transform of such quasilattices, Steinhardt was amazed to find that they reduce to series of delta functions in reciprocal lattice space—a result the crystallographers would only have expected for a truly periodic lattice. Unlike the Fourier transform of a true crystal, however, whose peaks are separated by finite intervals, the reciprocal space of a quasilattice turns out to be infinitely dense in diffraction peaks. But with finite intensity resolution one would not be able to tell the difference between diffraction patterns of a crystal and a quasicrystal—except that a quasicrystal diffraction pattern can exhibit forbidden rotational symmetry. The diffraction peak intensities observed by the NBS group are in good qualitative agreement with those calculated by Steinhardt and Levine. Penrose patterns, quasicrystals and their Fourier transforms all have the property of "self similarity"; the patterns repeat themselves on ever larger scales as the quasilattice grows.

Prospects. If the quasicrystal theory turns out to be a correct description of the new metastable state of bulk Al_6Mn, it will have explained the general symmetry properties of the quasilattice, but it does not uniquely specify the unit cells, nor how the actual atomic sites "decorate" the cells. That will require detailed treatment of the interatomic forces and a thermodynamic explanation of why they should seek out this metastable state. Steinhardt, Nelson and Ronchetti, making use of theoretical results obtained in 1978 by Shlomo Alexander and John McTague at UCLA, have already shown that the phase transition to the icosahedral quasicrystalline state would have to be of first order.

Just how pointlike the Al_6Mn diffraction pattern really is remains an open experimental question. With higher-resolution diffraction measurements now being carried out in several laboratories, it may turn out that the diffraction peaks are more diffuse than they first appeared to be, indicating that the bond-orientational order extends only over a finite correlation length.

But the data thus far and the theory point to a novel class of ordered structures in the solid state, neither glassy nor crystalline. Steinhardt suggests that we will have to do the quantum and classical mechanics of solids all over again. The nice, simple properties of crystals result from their periodic potentials. With quasiperiodic potentials, analogous properties arise, Steinhardt argues, but always a bit "bizarre." In place of a finite number of finite electronic band gaps, for example, one gets an infinite density of gaps. "Between every two band gaps there's another gap. That's a reflection of the self-similarity of these quasicrystals."

One will have to calculate in detail the electronic and elastic properties implied by the quasicrystal theory. Comparison with actual materials will then determine its relevance to the physical world. —BMS

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High-resolution photo of protoplanetary disk orbiting star

Before the summer of 1983 we had no serious evidence of nonstellar, solid material orbiting any star other than our own. As far as we knew, our solar system might be a rare—perhaps even unique—curiosity in the Galaxy. But in the last 18 months we've learned a lot. Infrared investigations by the Infrared Astronomy Satellite (IRAS) and several ground-based telescopes have provided strong evidence for aggregates of small particles orbiting as many as 40 stars in our extended neighborhood (PHYSICS TODAY, May 1984, page 17).

Convincing as these infrared data may be, they have not offered us an explicit "picture" of such a "protoplanetary" system. But now we finally have such a picture. Employing a highly sensitive charge-coupled-device camera with a sophisticated coronograph at the 2.5-meter Las Campanas Telescope in Chile, Bradford Smith (University of Arizona) and Richard Terrile (JPL) have produced a high-resolution image of a thin, Saturn-like disk of particules orbiting β Pictoris, a fourth magnitude southern-hemisphere star, 51 light-years (16 pc) distant from us. Smith made the CCD image public at the October meeting the American Astronomical Society's Division for Planetary Sciences in Hawaii.

The IRAS satellite, which ceased operation when it ran out of coolant at the end of 1983, had already produced evidence of a disk of cool material around β Pic, as well as similar systems orbiting the more prominent stars Vega and Fomalhaut. But IRAS was not capable of producing high-resolution, two-dimensional images. Operating at four far-infrared wavelengths—12, 25, 60 and 100 microns—with an aperture of 0.6 meters, the IRAS telescope offered a resolution of only 20 arcseconds. The β Pic infrared enhancement observed by IRAS was about 400 astronomical units wide, subtending (at a distance of 16 parsecs) an angle of less than 30 arcseconds, not much larger than the IRAS resolution limit. (One AU is the mean distance from the Earth to the Sun.)

With this very limited resolution, dictated by the small telescope aperture and the long wavelengths at which the thermal spectrum of the cool orbiting material peaked, IRAS was limited to sweeping the image of the stellar system across a narrow, unsegmented infrared detector. In this way the IRAS group measured a vaguely elliptical extended source of excess infrared radiation at least 400 AU wide in one direction and narrower than the resolution limit in the orthogonal direction. Beyond this rough measurement of the extent and aspect ratio of the circumstellar aggregation, very little could be said about the spatial distribution of its material, except to point out than an atypically high intensity observed at 12 microns (the shortest wavelength) suggested some relatively warm material orbiting rather close to the star. The IRAS image does not provide sufficient detail to tell whether the circumstellar system is a disk or a shell of matter.

The CCD camera employed by Smith and Terrile faced a very different situation. Observing at 8900 Å, just beyond the visible, with a telescope aperture more than four times that of IRAS, their angular resolution was limited only by atmospheric turbulence—on the order of one arcsecond—rather than the diffraction limit of the telescope. With the β Pic circumstellar image much larger than their seeing limit, they were thus able to produce a detailed "photographic" image with a CCD detector—a two-dimensional array of microelectronic photodetectors.

Their CCD detector is a 500×500 array of tiny photodiodes on a semiconducting chip less than a centimeter squared. Each of the 15-micron-wide pixels covers 0.46 arcseconds—roughly one resolution element.

Although going to short wavelengths improves the resolution, it introduces a major problem with which IRAS did not have to contend. IRAS was looking at thermal emission from the cool circumstellar material at far-infrared wavelengths where the star's own radiation is negligible. Smith and Terrile, on the other hand, chose to image starlight scattered from the circumstellar particles at near-visible wavelengths. In this case the glare from the star itself, which is overwhelmingly brighter than the faint circumstellar image, presents the principal difficulty. Their challenge was to image a circumstellar structure ten thousand times fainter than the star itself.

Coronograph. To get rid of as much of the blinding starlight as possible, the CCD camera employs a coronograph developed at the University of Arizona as part of an ongoing study of faint objects near the Jovian planets of our own solar system. The central element of the coronograph is an occulting disk, which masks the image of the overwhelmingly bright central object, in this case β Pic.

But an occulting disk is not nearly enough. It only intercepts β Pic starlight going straight through the atmosphere and the telescope optics. Starlight diffracted by the telescope can sneak around the occulting disk and still overwhelm the very faint circumstellar image. The coronograph therefore has an auxiliary optical system of its own, designed to eliminate as much of the scattered and diffracted starlight as possible. One must then process the image to subtract off the remaining background of sky-scattered starlight. Obtaining a measurement of the starlight background sufficiently accurate to perform this subtraction requires that the CCD detectors be sensitive over a dynamical range of four orders of magnitude.

This image processing is, however, much simpler than the elaborate deconvolution techniques required by the ground-based-telescope groups that had previously found near-infrared evidence for a circumstellar system around HL Tauri. Because that star is ten times farther away than β Pic, these groups were forced to employ speckle interferometry or maximum-entropy image enhancement to measure this extended source at the very limit of angular resolution (PHYSICS TODAY, May 1984, page 19). Smith and Terrile, by contrast, had resolution to spare. Their problem was stellar glare.

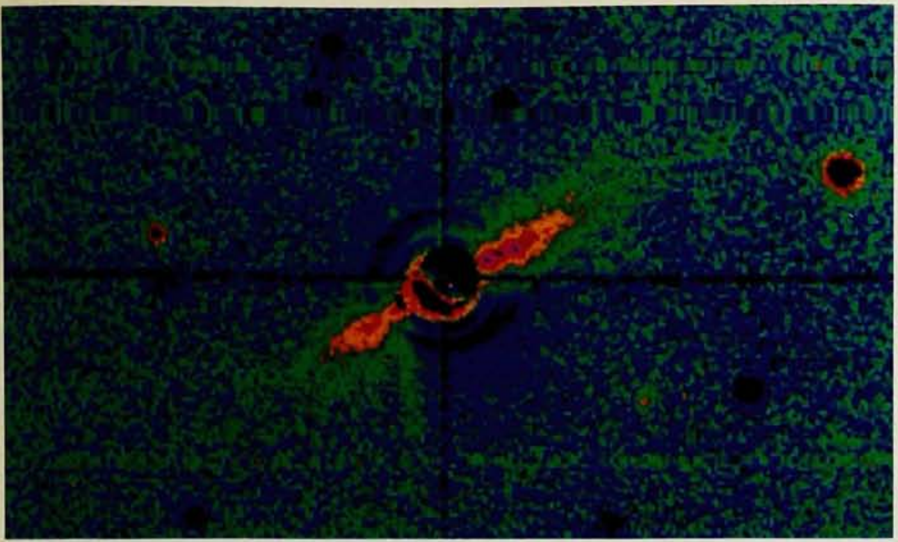
"Even with the coronograph," Smith and Terrile tell us, "the scattered light from β Pictoris is still 3–5 times brighter than the circumstellar disk.... Were this not the case, the disk would surely have been discovered long ago, using conventional techniques with optical telescopes."[1] The CCD camera used by Smith and Terrile is a development instrument made available by the Wide-Field/Planetary Camera Investigation Definition Team, headed by James Westphal (Caltech). A similar camera is scheduled to be incorporated in the Hubble Space Telescope (PHYSICS TODAY, November, page 17).

The image. The first thing one notes in the image produced by Smith and Terrile is that the circumstellar system appears extremely thin. One might imagine it to be a pair of jets expelled from the stars in opposite directions. This interpretation is however untenable. β Pic is a stable, well behaved, main-sequence A class Star. It is most unlikely that such a star would emit 400-AU-long jets of particulate material. Even gas jets of such extension are out of the question. Its far-infrared spectrum, as measured by IRAS, was clearly thermal radiation from particulate matter rather than gas.

It seems clear, therefore, that Smith and Terrile are seeing a very flat disk of orbiting circumstellar material almost precisely edge on. The disk extends 400 astronomical units from β Pic in each direction. Thus, imaging scattered starlight at near-visible wavelengths, Smith and Terrile are sensitive to material considerably farther out than is the IRAS detection of far-infrared thermal radiation.

They are also able to measure the thickness and brightness of the disk as a function of distance from the star in much greater detail than IRAS. The thickness of the disk increases somewhat with distance from the star. At 300 AU it is 50 AU wide. Because of the coronograph's occulting disk, Smith and Terrile cannot see within 100 AU of the star. Beyond that distance they find that the brightness fall-off of the scattered light fits well to an R^{-3} dependence of the density of scattering particles on the distance R from β Pic.

If one extrapolated this observed R^{-3} particle density variation in to the unseen 100 AU nearest the star, one would conclude that the disk is optically thick—obscuring the star almost completely for an observer looking edge on through the disk. But in fact, β Pic appears to us only about 40% fainter than other stars of its spectral class. This implies that the disk is optically *thin*—that the R^{-3} increase of particle density as one approaches the star does not continue all the way in. Smith and Terrile conclude from the disk's failure to dim the star more than half a magnitude that an inner region of radius 30 or 40 AU is largely free of



Circumstellar protoplanetary disk of particulate matter orbiting the star β Pictoris, 51 light-years from us, appears edge-on as two gigantic arms extending 400 AU from the star. The large central dark spot is an artifact due to the sophisticated occulting coronograph needed to kill the glare from the star. This high-resolution photographic image, at 8900 Å, was made by Bradford Smith and Richard Terrile with CCD detectors at the Las Campanas 2.5-m telescope.

scattering particles.

The particle orbits in the disk appear to be very coplanar. Inclinations with respect to the disk plane do not exceed 5°. This small spread of inclinations is comparable to that of the planetary orbits of our solar system.

Interpretation. The clear area at the center of the disk is comparable to the size of the solar system. If planets have already formed in this inner region, Terrile told us, one would expect it to be relatively clear of small particles, as is our solar system. Planetary formation is believed to take place on a time scale of 10^8 years.

Like Vega and Fomalhaut, β Pic is a main-sequence, A class star. One knows only that such a star is somewhere between 3×10^6 and 10^9 years old. If β Pic is much less than 10^8 years old, Terrile explains, we are probably looking at a protoplanetary system. If, on the other hand, the star's age exceeds 10^8 years, we may be seeing the remnant disk of a young planetary system. The flatness of the disk argues against its being very much older; large planets would eventually disperse the small-particle debris in the direction transverse to the disk plane.

Planets already formed could not be seen by the present coronograph. Because of their small surface-to-volume ratio, the scattered light from Jovian planets would be very faint. To see them against the stellar glow would require a dynamical range of 10^9—an order of magnitude wider than the capabilities the present coronograph and detector system.

Does our own solar system have a remnant disk of small particles similar to that of β Pic beyond the orbit of Pluto? No such disk has been seen. On the other hand, we would have difficulty seeing such dark, cold material in the outer reaches of our solar system. But having seen none, Terrile argues, we probably have less than β Pic. Recalling that our five-billion-year-old system is much older than β Pic, he suggests that ours may have been dissipated long ago.

Having thus far observed at only one wavelength, Smith and Terrile have as yet produced little new information about the size distribution of the scattering particles. They plan soon to extend their imaging to visible wavelengths. From the fact that the stellar spectrum is not reddened by scattering off the disk, they deduce that the scatterers are at least tens of microns across. Particles as small as ten microns, however, will be removed from circumstellar orbit by the Poynting–Robertson effect on a time scale of 10^8 years: Losing angular momentum as they radiate, the particles eventually spiral into the star. Even if β Pic is only 10^7 years old, the Poynting–Robertson effect might explain the absence of particles smaller than 100 microns in the inner 30 AU of the disk. The apparent absence of particles larger than a millimeter in this inner region, Smith and Terrile argue, can only be explained by planetary accretion.

The material of the disk particles is presumed to be primarily silicates, carbonaceous materials and ice. Not knowing the size distribution of particles—which can presumably range from microns to kilometers—Smith and Terrile can give only a very broad estimate of the mass and angular momentum of the disk. Beyond 100 AU, they estimate, the total mass is a few hundred Earth masses, and the angular momentum is about 10^{-4} times that of the star itself.

Others. "This is only the first circumstellar system we've looked at," Smith told us. IRAS has already found far-infrared evidence for the existence of about 40 such systems at distances close enough to be imaged in detail at shorter wavelengths by this sensitive new technique. "Unfortunately," says Smith, "the IRAS people are not yet telling where most of these 40 systems are. We'd like to have a look too."

Stellar astronomy, Terrile reminds us, has learned about stellar evolution by looking at a great many stars of different ages. Planetary astronomy appears now to be on the verge of a similar proliferation. With only a single example of a solar system at our disposal, our powers of inference have until now been very limited. From what has been seen in the last two years, it appears probable that planetary systems are quite abundant.

The first explicit detection of a planetary companion to any star other than our own was reported[2] just two months ago. Donald McCarthy, Ronald Probst and Frank Low (University of Arizona) used one-dimensional speckle interferometry in the near infrared to detect a massive cool companion 7 AU from the star VB 8, 21 light-years distant in the constellation Ophiuchus. This historic observation was facilitated by the fact that VB 8 is an unusually cool star and the companion is an unusually hot substellar object. With a mass at least ten times that of Jupiter, the companion has a surface temperature of 1360 K. Its luminosity, in fact, exceeds what one would expect for a Jovian planet of such a mass. Given its extraordinary mass and luminosity, McCarthy and his colleagues have for the moment given it the cautious appellation "brown dwarf." But the companion is clearly not massive enough to be a star, Low assures us.

The detection of a planet no more luminous than Jupiter, orbiting a star like our own, Terrile suggests, will require a highly sensitive coronograph system with an orbiting telescope specifically designed to minimize scattered and diffracted light. "These things are not all that faint. The problem is the optics. You're looking for objects next to stars a billion times brighter." One needs to push the present system, which can already range of 10^8, by just one more factor of ten. Smith and Terrile would like to accomplish this with a suitably designed telescope in the next five years. —BMS

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