Hence the stability of indirect reciprocity is based on a rather subtle equilibrium between different strategies. This may be why Wedekind and Milinski did not find significant correlations between payoffs and scores.

Keeping track of scores is important for both direct and indirect reciprocation. Actually, some evolutionary psychologists believe that selection has provided us with a special knack for doing exactly that (*11*). Other "mental modules," like our language instinct or our faculty for recognizing faces, work to the same purpose. The information flow within the social group is all-important; we feel cheated when our good deeds go unnoticed, and refrain from bad deeds lest they become known. The very symbol of moral pressure is the ever-watchful eye in heaven, and conscience acts as an internalization of our standing with others.

More than a hundred years ago, a Viennese playwright identified a root of social injustice in the unfortunate fact that rich people tend to invite for dinner other rich people, rather than the poor. In the eyes of evolutionary biologists, this is direct reciprocation in action, based on the tacit expectation of a return invitation. But capitalists have also always been keen on philanthropy. This entails indirect reciprocity, as shown by the fact that donations are usually well advertised (see the figure), despite the biblical injunction to keep them secret—"The left hand should not know what the right hand is doing."

The fiction of a rational "homo economicus" relentlessly optimizing material utility is giving way to "boundedly rational" decision-makers governed by instincts and emotions (*12*). Economists and biologists are increasingly drawn to the natural history of economic life. Now we have arrived at a stage where formal models can be tested by experiment. Students of animal behavior (*13*), psychologists (*14*), and experimental economists (*15*) are approaching this task from different directions, each with the bias of a long tradition. We must hope that in this convergence of three fields, the left hand will know what the right hand is doing.

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PERSPECTIVES: PLANETARY SCIENCE

The Shape of Kleopatra

William K. Hartmann

The study of asteroid 216 Kleopatra by Ostro *et al.* on page 836 of this issue (*1*) serves as a reminder of the astonishing results that can come from ground-based observations of asteroids, even in an era when the NEAR spacecraft is orbiting asteroid Eros. Ostro *et al.*'s results are provocative in several regards, from fundamental insights into the composition and structure of Kleopatra to prospects of asteroid mining.

Ostro *et al.* use a unique and powerful technique for learning about interplanetary objects by bouncing radar waves off them. This not only allows a crude imaging of asteroid shapes but also sheds light on asteroid surface properties. When Ostro pioneered asteroid radar imaging in the 1980s and 1990s, the technique was so unusual that he had the field virtually to himself, because few were equipped to follow the path he was exploring (*2*). The popular media likes to give coverage to NASA space missions to asteroids (or, arguably with even greater enthusiasm, to NASA failures). But few nonspecialists will know that Ostro has produced images of oddly shaped asteroids with craters clearly visible on their surfaces by ground-based radar.

An important aspect of the new work reported in this issue involves the understanding of metal asteroids. Since the 1970s, astronomers have grouped asteroids into various "taxonomic classes" that seem to correspond to the types of meteorites that fall on Earth, such as primitive, never-melted rocks, lavalike basaltic rocks, olivine rocks, chunks of nearly pure nickel-iron metal, and mixed stony-iron rocks. But more specific matches between asteroid classes and meteorite types will remain uncertain until samples are returned from asteroids or in situ analyses with landers are performed. So-called M-class asteroids, like Kleopatra, are a case in point. They are thought to match metal-rich meteorites, but metals have few diagnostic spectral absorption features. Ostro *et al.* use a two-step argument to claim that Kleopatra is a giant mass of metal and metal fragments. First, the radar constrains the surface bulk density to be 3.5 g/cm^3, which could match either solid rock or ground-up metal powder with a porosity of less than 60%. Second, the radar reflections show that the surface is not rough, like broken rock, but smooth, like powder lying in repose. The authors thus argue that the surface is covered by metallic powder with a porosity matching that of the powdery regolith on the moon, produced by eons of meterorite sand-

Early conceptual models for the highly elongated asteroid 624 Hektor. Hektor has a similar shape to Kleopatra and may have a similar structure and origin. Hartmann and Cruikshank (*9*) discussed the possibilities that this asteroid formed a single, elongated fragment (**top**), or a compound binary consisting of two strong, spheroidal bodies (**middle**). Weidenschilling (*10*) described how a weak, spinning contact binary could deform into two elongated lobes (**bottom**). The work of Ostro *et al.* suggests this general shape with a narrow neck possibly affected by impact erosion and redistribution of debris.

The author is at the Planetary Science Institute, 620 North Sixth Avenue, Tucson, AZ 85705–8331. E-mail: hartmann@psi.edu

blasting. It is intriguing to imagine a 217-km-long asteroid knee deep in powdered metal.

Ostro *et al.* also provide direct confirmation of an extraordinary dumbbell shape for Kleopatra, as already indicated by the brightness variations when it rotates. The images show an object shaped like a dog's bone, with lumps at each end. Other such asteroids of other taxonomic classes are also known. I suggested that a range of asteroid peculiarities, from occasional dumbbell shapes to asteroid satellites, could be a result of the catastrophic events that produced most asteroids as fragments of once larger parent bodies (*3*, *4*). The idea is that adjacent fragments moving nearly parallel in the chaotic expanding cloud of debris after a collision find themselves within each others' gravitational sphere and either fall together at low velocity (making a dumbbell-shaped object) or end up orbiting each other (producing an asteroid with a satellite) (see the figure). Some computer models (*5*) offer support for this idea. On the other hand, if Kleopatra's shape, as reconstructed from the radar data by Ostro *et al.,* is correct, it raises the question of how such a spectacularly long "neck" could form between the two lumpy objects, if they started out as a contact binary. Conceivably, impact erosion may have reduced the size of the two initial bodies and at the same time filled in the point of contact between them, thus producing Kleopatra's shape.

A final point of interest in the work of Ostro *et al.* is more visionary. Ostro *et al.* conclude that Kleopatra is a 217-km-long piece of nickel-iron, possibly in the form of chunks or broken masses, covered with a fine powder of pulverized metal grains or dust. In other words, the asteroid is an easily harvestable ore body floating in the sky. Half a century ago, the idea of mining asteroid resources was firmly in the realm of science fiction. However, in 1977, Gaffey and McCord noted (*6*), on the basis of early asteroid spectroscopic taxonomies, that some asteroids are probably metallic and pointed out that even kilometer-scale bodies of this sort could have enormous economic value. If the cost of interplanetary operations decreases as space capabilities are developed further, and the cost of raw materials increases as we use up Earth's resources, then the recovery of asteroid metal resources may become economically attractive (*7*). These resources include not just nearly pure nickel-iron alloys, such as seen in "iron" meteorites, but also other metals, such as platinum group metals, which are concentrated in other types of meteorites (and presumably asteroids). One of the difficulties has always been the question of how to harvest or process these high-strength metal materials. However, the work of Ostro *et al.* portrays a giant metal asteroid with enough gravity to retain a regolith of metal powder. The nickel-iron could be scooped up or gathered with a simple magnetic rake.

The idea of asteroid mining raises the question of who owns the resources. Is there a social mechanism by which the benefit of such resources can be spread to all humanity, instead of increasing sociopolitical instability by making only the discoverers (or discovering nations) rich and increasing the gap between the first and third worlds? Furthermore, should some asteroids be declared off limits to mining and set aside as scientific preserves, as suggested a few years ago by planetary scientist George Wetherill (*8*)?

The media tend to focus on the "asteroid threat"—the evidence that an asteroid may have wiped out the dinosaurs, the devastation that future modest-scale impacts could cause, and (relatively unproductive) schemes to blow threatening asteroids out of the sky with nuclear missiles. But time scales of global-scale threats are on the order of many millennia. The work of Ostro *et al.* moves us one step closer to capitalizing on the "asteroid opportunity," by investing in human capability to reach and explore asteroids over a time scale of a century in order to understand asteroid evolution, explore possible resource bases that would reduce the plundering of Earth, and develop the ability to deflect Earth approachers from dangerous paths.

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PERSPECTIVES: PLANT BIOLOGY

Lighting Up the Nucleus

Akira Nagatani

A wide range of physiological and developmental processes in plants, such as seed germination, greening of seedlings, and flowering, are regulated by light. Thus, to increase their productivity and fitness plants must be able to detect and adapt to changes in light stimuli. They have skilfully achieved this by evolving light detecting photoreceptors, of which the best characterized are the five members of the phytochrome family. Phytochromes are water-soluble chromoproteins of ~120 kilodaltons that consist of a tetrapyrrole pigment molecule (which traps light photons) covalently attached to a polypeptide backbone (*1*). Since their discovery, enormous efforts have been devoted to elucidating how phytochromes transduce light stimuli into molecular signals that culminate in the expression of light-activated genes. Now, on page 859 of this issue, Quail and colleagues (*2*) present compelling evidence that phytochromes are recruited to the nucleus and bind to the promoters of light-activated target genes, regulating their expression. These findings demonstrate that plants have invented an extremely simple and efficient way of modifying gene expression in response to changes in light.

The author is in the Department of Botany, Graduate School of Science, Kyoto University, Kitashirakawa, Kyoto 606-8502, Japan. E-mail: nagatani@physiol.bot.kyoto-u.ac.jp

The inactive form of phytochrome absorbs red light and is activated; when the activated photoreceptor absorbs far-red light it is converted back to the inactive form. Present in all plants, phytochrome homologs have been found recently in photosynthetic cyanobacteria, but not in yeast or animals (although photoreceptors called cryptochromes have been found in flies and mammals). Phytochromes were thought to reside in the cytoplasm of plant cells, but this has turned out to be only half true because, when activated by light, they accumulate inside the nucleus (*3*, *4*).

Molecular genetic analyses have hinted that the nucleus might be the site of light-activated signal transduction (*5*). Putative components of the light signaling pathway have been identified by analysis of plant mutants that show changes in morphology usually associated with light, in the absence of a light stimulus. Some of these components are nuclear proteins of unknown function. More recently, mutants specifically deficient in phytochrome signaling have been isolated and mutations identified in *spa1* and *far1,* two genes that encode nuclear proteins.

Phytochromes contain a core signal transduction domain within their carboxyl-terminal region (*6*), and yeast two-hybrid screens have identified three proteins—PIF3 (*7*), PKS1 (*8*), and NDPK2 (*9*)—that interact with this region. Interestingly, their predicted functions and subcellular localization are different. Originally identified by Quail's laboratory,