rare-earth atom can be seen in the depression of the superconducting transition temperatures. The results are given in Fig. 1.

For rare earths dissolved in pure La the maximum depressions occurred for Ce and Gd, reaching 6°K/atom percent at Gd. For rare earths dissolved in $ZrB_{12}$, on the other hand, there is only one very pronounced maximum which occurs for Pr, reaching close to 13°K/atom percent. The magnitude of this maximum points to a virtual bound $f$-level in Pr, very near to the Fermi surface. This leads us to expect that Pr in $ZrB_{12}$ will also exhibit a resistance minimum, and this is verified in Fig. 2.

Based on an extrapolated lattice constant for hypothetical $PrB_{12}$ of 7.53 Å, the pressure at the Pr site in $ZrB_{12}$ is roughly 200 kb, if we assume that the compressibility of $ZrB_{12}$ is the same as that of pure crystalline boron. At this pressure, Ce is tetravalent and no longer magnetic; this is evidenced by the small depression of the superconducting transition temperature and the lack of any resistance minimum. However, Pr could be either tetravalent with a virtual bound $f^1$ configuration or trivalent with a virtual bound $f^2$ configuration. We expect an $f^1$ configuration to have an effective magnetic moment of $\sim 2.5$ Bohr magnetons, whereas an $f^2$ configuration should have an effective magnetic moment of $\sim 3.6$ Bohr magnetons. Inverse magnetic susceptibility versus temperature follows a clean Curie law and gives a value of close to 3.6 Bohr magnetons, thus favoring the $f^2$ configuration.

ZACHARY FISK
BERND T. MATTHIAS*
*Institute for Pure and Applied Physical Sciences, University of California at San Diego, La Jolla*

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* Also of Bell Telephone Laboratories, Murray Hill, New Jersey 07971.

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## Destruction of Pacific Corals by the Sea Star Acanthaster planci

Abstract. Acanthaster planci, *a coral predator, is undergoing a population explosion in many areas of the Pacific Ocean. Data on feeding rates, population movements, and stages of infestation were collected along coral reefs of Guam and Palau. Direct observations on destruction of Guam's coral reefs indicate that narrow, fringing reefs may be killed as rapidly as 1 kilometer per month. In a 2½-year period, 90 percent of the coral was killed along 38 kilometers of Guam's shoreline.*

Goreau (*1*), in seeking causes for impoverished coral growth in areas of the Red Sea, suggested that predation by a large, sixteen-armed, spiny sea star, *Acanthaster planci* (Linnaeus), the "crown-of-thorns starfish," might be sufficient explanation. Barnes and others (*2*) reported that the same species was destroying large tracts of living coral along the Great Barrier Reef in Australia. Recently *A. planci* was reported from several Pacific islands (*3*). A severe infestation on the reefs of the U.S. Territory of Guam has led to the establishment of a control program under the direction of the University of Guam. Available information indicates that recent population explosions of *A. planci* are occurring almost simultaneously in widely separated areas of the Indo-Pacific Ocean and that these are not short-term population fluctuations of the type reported for numerous other marine invertebrates (*4*).

Although *Acanthaster planci* is a Linnaean species and has been known for a long time, it has been regarded as a great rarity until about 1963, when large swarms were reported by local residents from the Great Barrier Reef near Cairns.

Since 1967 this starfish has killed well over 90 percent of the living coral along 38 km of the coastline of Guam from just below low spring tide level to the depth limit of reef coral growth (about 65 meters). After the death of the coral polyps, the coralla are rapidly overgrown with algae. Most fish leave the dead reefs, with the exception of small, drab-colored, herbivorous scarids and acanthurids.

Other animals feed on coral (*1*), but none so efficiently as *A. planci*. Caged, starved specimens ate mollusks and other echinoderms, but observations showed scleractinian corals of any configuration as the primary diet of undisturbed specimens. Hydrocorals and octocorals were eaten only after the madreporarian corals were gone. *Acanthaster planci* feeds by everting the gastric sac through its mouth, spreading the membranes over the coral, and digesting the soft tissues in place (*1–3*). The skeleton left behind stands out sharply as a patch of pure white until overgrown with algae. On reefs with low *A. planci* densities, feeding was nocturnal and specimens were cryptic during daylight. On reefs with high densities, many animals were found feeding during the day (Fig. 1).

Although *A. planci*, 60 cm in total diameter, were collected, those in the infested areas of Guam averaged 24.2 cm across the arms and 13.8 cm across the disk. The daily feeding rate was observed to be twice the area of the disk. Coral is therefore killed in areas of infestation at a mean rate of 378 $cm^2$ per animal per day or about 1 $m^2$ per month. In some localities, with population densities as high as one animal per square meter of reef, all living coral would be eaten in 1 month.

Before 1967, *A. planci* was not common on Guam (*5*). In early 1967, the starfish became abundant on reefs off Tumon and Piti bays (Fig. 2). They were observed feeding actively at depths of 3 to 10 m. The numbers of sea stars increased rapidly, and they were observed in deeper water. Large parts of the reef were completely stripped of living coral before the sea stars moved to adjacent areas. By spring, 1968, almost all of the coral off Tumon Bay was dead. In September of 1968, *A. planci* had spread to Double Reef, and in November divers removed 886 animals from 90,000 $m^2$ of reef at that locality. At that time, half of the coral of this reef was dead. Coral to the north of Double Reef was alive, although *A. planci* was present in limited numbers. Hazardous weather prevented surveillance of this area from December until late March. By then, the reef was dead for another 4 km, and the main concentration of animals had moved to an area extending 3 km southeastward from Ritidian Point.

Strong wave surge along this northern shoreline prevented the sea stars from entering shallow water until late

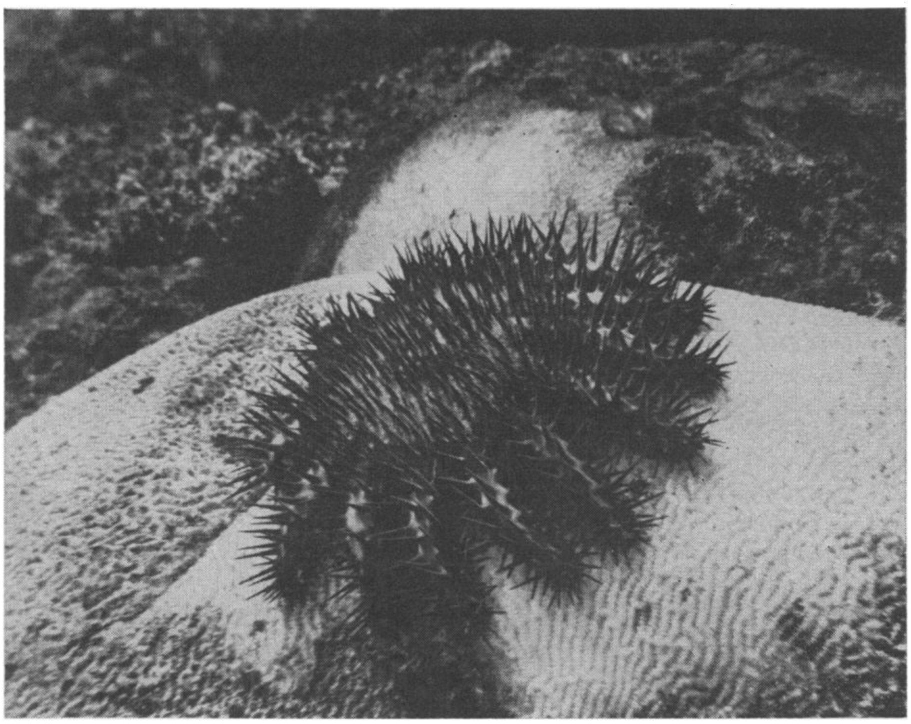

Fig. 1. *Acanthaster planci*, normally a nocturnal coral predator, often feeds during daylight in regions of high population densities.

March. The sea stars were observed circumnavigating Ritidian Point in water over 30 m deep, along a flat coralline pavement. During April, the main front of sea stars moved into shallower coral reefs as wave action decreased. In late April, dense concentrations were present at the lower edge of the northern fringing reef at a depth of 20 m. Coral destruction was extensive.

An underwater survey of the entire area between Orote Point and Ritidian Point during April and May showed that over 90 percent of the reef coral was dead from low spring tide level to the limit of coral growth. Living coral was found only along the shallower, more exposed parts of the coastline.

The larger, rounded, massive corals such as *Porites lutea* survived to depths of over 3 m. The tops of these coral heads were alive, but the lower portions were eaten, presumably because *A. planci* apparently could not maintain a hold on the evenly rounded coralla in the face of strong surge movements. Both the coral and the sea star produce mucus during the feeding process (*1*) which decreases the holding power of the asteroid tube feet. Specimens feeding on this type of coral in protected areas or during calm seas were easily dislodged, whereas they are difficult to dislodge when they can wrap themselves around a projection. With the exception of these few corals, the only living reef-building coelenterates were *Millepora* and octocorals, which were attacked only after stony corals had been eaten.

Specimens of *A. planci* marked with anchor tags (*5*) moved as far as 250 m per week. However, movement was slower when the starfish were feeding.

Movement of populations is inferred from disappearance, by March 1969, of *A. planci* from Tumon and Piti bays where large numbers had previously been observed and by the appearance of large numbers of adults in previously uninfested areas. After eating most of the coral, the starfish spread north and south, killing the reef as they went. Observations of the advancing "front" showed that the population density was as high as one animal per square meter along a 2.5-km section of coastline (Fig. 3). Here the starfish were arranged in a relatively narrow, irregular band 5 to 20 m wide parallel to the coastline. Long bands sometimes broke up into groups that moved as amorphous herds of 20 to 200 individuals.

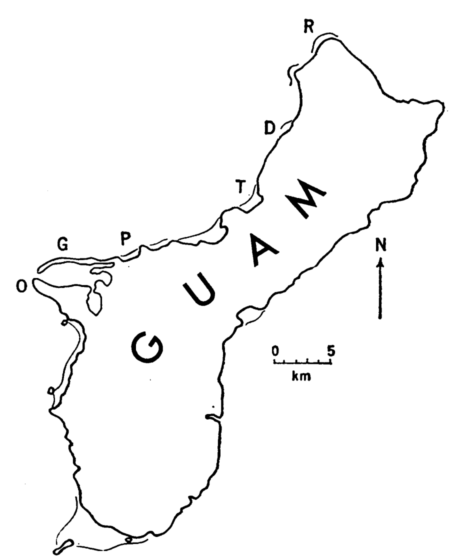


Fig. 2. Diagram of Guam; *R*, Ritidian Point; *D*, Double Reef; *T*, Tumon Bay; *P*, Piti Bay; *G*, Glass Breakwater; *O*, Orote Point.

Depth was no barrier to movement, but soft substrates were avoided. Sand, moved by surge action, was an effective obstacle, since patch reefs surrounded by sand in areas of strong wave action were not infested. Sand provides no gripping surface for the tube feet, and the sea stars are easily overturned by water movements. In protected areas or during calm seas, sand is not a barrier.

Estimation of size of population and severity of infestation is difficult because the animals hide in crevices during the day, particularly in reefs with well-developed coral. In areas of poor coral development, animals are easier to count, except when herding. Population size can be estimated from numbers of animals seen during a particular time period. In normal reef environments, a diver observes less than one specimen per hour of search. In infested areas, the number is generally more than five per hour and can be as high as 100 per 10 minutes. In conditions of infestation, several individuals may congregate on a single corallum, and as many as 12 have been found completely covering a coral head.

Reasons for the sudden increase of population are obscure. Depletion by shell collectors of the triton shell *Charonia tritonis*, a predator of *A. planci*, has been implicated as a possible cause of the outbreaks (*7*). My studies indicate that predation by *C. tritonis* would not result in adequate control of *A. planci* populations. Two specimens of *C. tritonis* (29.5 and 36.8 cm in length of shell) were put together with *A. planci* in a large penned-in area of a living reef. At night, the triton actively sought out sea stars and could detect the presence of its prey from a distance of at least 1 m. When contact was made, the sea stars rapidly moved away, but the triton usually managed to attach itself to the aboral side of the disk with its proboscis and pull itself up onto the sea star. However, often only half of the sea star was eaten, the attached part being autotomized, and the remainder escaped and lived to regenerate lost parts. Regeneration of small functional arms required about 2 months. One triton attacked only one adult sea star per 6 days, even when an unlimited supply was available. *Charonia tritonis* does not prey solely on *A. planci* but also attacks *Culcita novaeguinea* and *Linckia laevigata* when these are available, and the chance of survival of its prey is large.

Even if the triton were abundant, it is doubtful that it could control *A. planci*. Depletion of other gastropod predators, such as *Murex* and *Cassis*, which might feed on *A. planci* under natural conditions does not seem to be the cause of the infestations. Large populations of the sea stars occur in parts of Palau and Rota which are seldom visited by shell collectors and where these gastropods are common.

In seeking a cause for the sudden appearance of large numbers of adult *A. planci*, early life stages must be considered. The greatest mortality must occur during the larval stages. Shallow-water tropical Pacific substrates, where the larvae can survive after settling, are solidly encrusted with filter feeders (such as corals) capable of eating the larvae. Destruction of reefs by blasting, dredging, and other human activities has provided fresh surfaces, free of filter feeders, for settlement of the larvae. In such areas original populations of several hundred animals, concentrated together, might provide the necessary seed population for an infestation. Such dead coral areas must probably be freshly provided during time of larval settlement (December and January in Guam). Infestations in Guam, Rota, and Johnston Island were first noted near blasting and dredging activities.

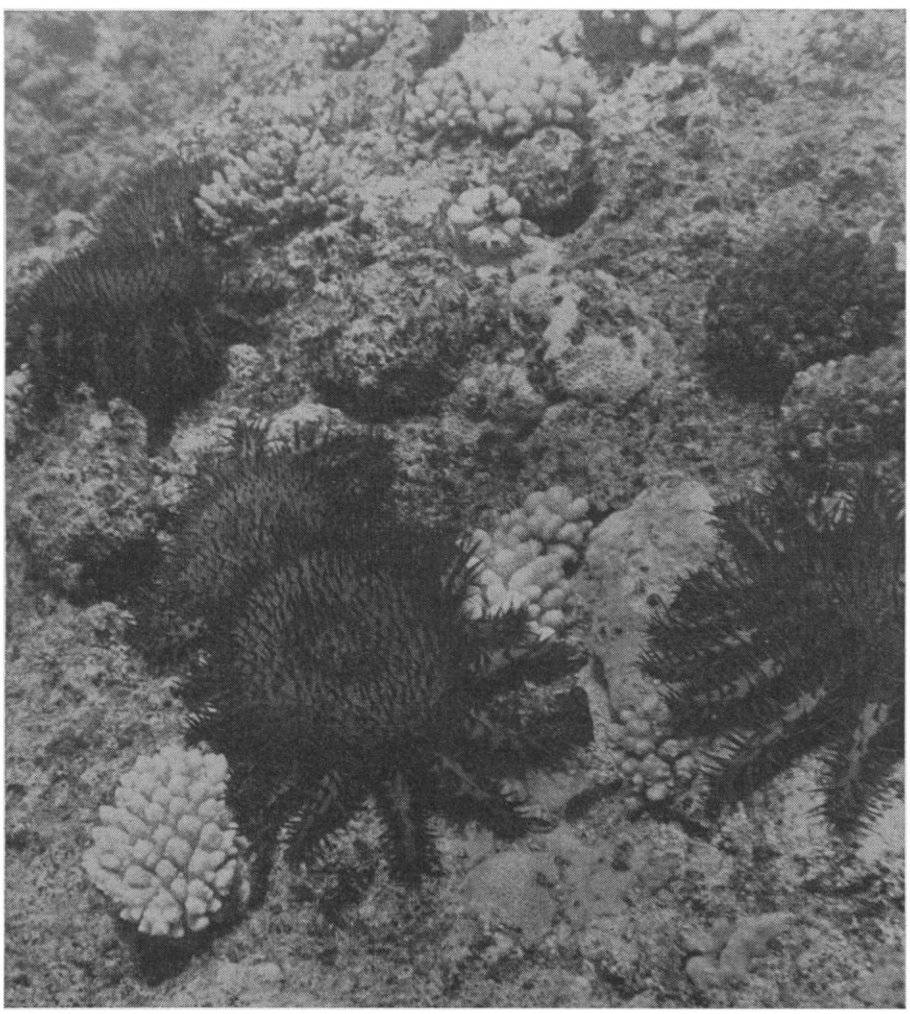

Fig. 3. A small portion of the advancing wave of *A. planci* that has eaten almost all coral along the northwestern sector of Guam. Densities as high as this extend along a 2.5-km section of Guam's coral reefs.

For the second phase of infestations we must assume that *A. planci* larvae can, like many marine invertebrate larvae (*8*), seek out adults near which to settle. Coral recently killed by adult starfish provides excellent settling areas for larvae. Concentrations of adults would provide areas of attraction for larvae, resulting in localized recruitment. Support for this hypothesis was gained by the appearance in March and April 1969 of large numbers of small *A. planci* (3 to 6 cm in diameter) at Double Reef, the northernmost region of infestation during the breeding season of November and December. Juveniles are not abundant elsewhere, indicating either that the larvae are attracted to feeding adults or that areas of feeding adults permit the highest survival of young.

Control of infestations requires that adults be prevented from infesting new coral areas. If infestations are discovered at an early stage, control is simplified because the seed populations are localized and the animals are easy to find. At a later stage topographical zones must be found to establish zones through which the sea stars cannot move. Containment of adults within areas delimited by these zones will result in a natural, rapid decline of the population through starvation. After a period of 1 or 2 years, remaining animals could be removed.

Where suitable zones cannot be set up, sections of the reef may be preserved by extermination in local areas (*2*). Major reef sections or islands connected by shallow waters to other coral zones could be isolated, if possible, to prevent migration to nearby reefs. Such migrations are most likely to occur after complete destruction of the infested zone. Adults have an estimated life span of about 8 years, but, when deprived of living coral, they starve in about 6 months.

On Guam, where narrow, fringing reefs are common, areas in advance of the population movement were selected, and migration over these zones was prevented by weekly inspections of about 2 km of coastline. Divers were towed behind a boat, and any sea stars found were then killed with Formalin (5-mc injection, full strength).

*Acanthaster planci* have not been

killed between the barriers. The sooner they finish what live coral remains, the sooner death through starvation will occur. It is important that this happen prior to the influx of larvae in the fall, or control activities may have to be extended for an additional year.

Destruction of living coral reefs would be an economic disaster for small isles and atolls of Oceania. Most inhabitants of Oceania derive almost all their protein from marine resources, and destruction of living reefs results in the destruction of fisheries. Eventually, loss of living corals would allow severe land erosion by storm waves.

Information concerning infestations in other areas of the Pacific is urgently needed. Reports of infestations have come from islands off Mersing on the east coast of Malaysia, from Borneo, New Guinea, Fiji Islands, Truk, Palau, Yap, Rota, Sipan, Wake, Johnston Island, the Great Barrier Reef, Midway, and Guam. With the exception of Guam, Australia, and Palau, the extent of the infestations is not known. Guam's infestation began only a little more than 2 years ago. Palau is in an early stage of infestation. Truk has had a heavy infestation for less than a year. Researchers working in the Pacific are requested to notify the author of normal populations or abnormal concentrations of *A. planci* and the degree of coral damage. Pertinent data on recent dredging or blasting activities or dynamiting for fish should be noted.

Long-term control may be possible by monitoring of areas subject to blasting or dredging during periods of larval settlement. Seed populations can be eliminated before larval settlement in the following year. If, however, the population explosion is due to a basic change in the life history of *A. planci*, control will probably not be possible. Geological records clearly indicate that large groups of animals have become extinct within a relatively short time. Rugose corals offer an excellent example. The appearance of an overly efficient predator might cause such extinction. Wholesale destruction of madreporarian corals has been witnessed during the past few years. This destruction may continue to the point where the coral fauna cannot recover. There is a possibility that we are witnessing the initial phases of extinction of madreporarian corals in the Pacific.

RICHARD H. CHESHER
*University of Guam, Agana, Guam*

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20 May 1969

## Y-Modulation: An Improved Method of Revealing Surface Detail Using the Scanning Electron Microscope

A Stereoscan Mark II scanning electron microscope is now in use in the geology department of Imperial College of Science and Technology. Until now, the instrument has been used for looking at, and photographing, a variety of subjects from the realms of paleobotany, micropaleontology, biology, chemical technology, and metallurgy. This parallels work in progress on similar instruments elsewhere.

Recently, the instrument was fitted with several accessories newly developed by the manufacturers (Cambridge Instrument Company). These include the so-called scan rotation unit, which has several functions. In addition to the ability to rotate the direction of scan through 360° and to compensate for the apparent distortion introduced by the angle of tilt of the specimen table, it incorporates a magnification factor, continuously variable from × 1 to × 2.5, and the Y-modulation device which is the subject of this report.

As in normal scanning electron microscopy, a finely focused beam of electrons is deflected across the surface under investigation. The number of electrons back-scattered and emitted is a function of the topography and composition of the specimen (see Fig. 1); such electrons are accelerated by a wire grid biased to + 12 kv and allowed to strike the surface of a phosphor screen. The scintillation produced is viewed and amplified by a photomultiplier and the output of the photomultiplier is applied to a cathode-ray tube scanning in synchronization. The scan size of the cathode-ray tube remains fixed at 10.5 cm², but the area of scan on the specimen may be successively decreased, thus giving an apparent step-up of magnification within the range of × 20 to × 100,000 at the normal working distance of 11 mm. These values may be varied either by changing the working distance or by utilizing the zoom magnification factor on the scan rotation unit.

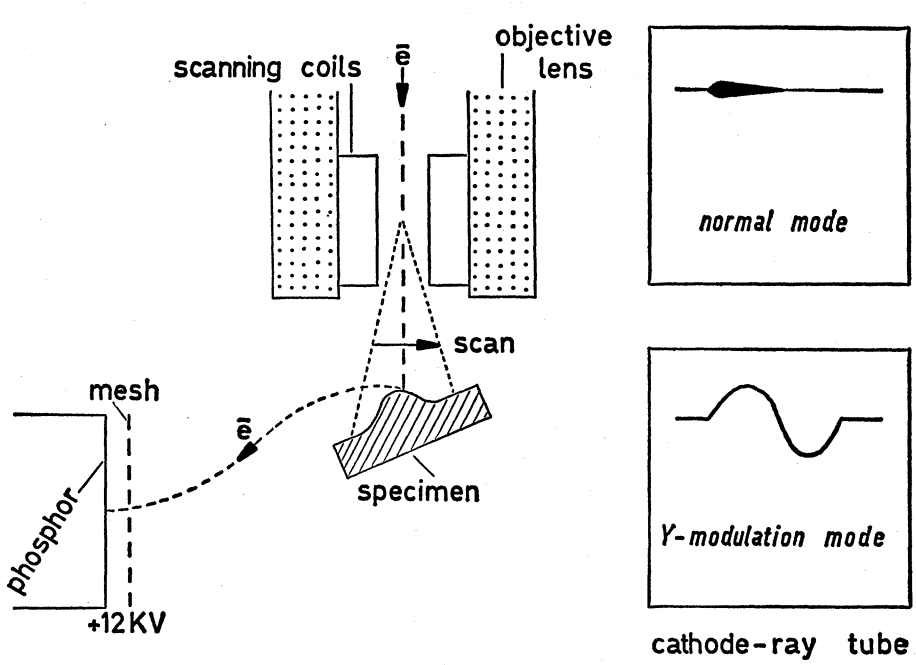


Fig. 1. Comparison between normal mode and Y-modulation mode as a function of topography.