Chapter 3

Radiotics (= The Science of Radial Structures)

The task of *radiotics*

This new branch of biology which, considering its multiple connections with *crystallotics*, has special significance for the understanding of “crystal souls”, includes the whole natural history of the Radiolaria or “radiants”. Although our *radiotics* is rich in remarkable facts and is fruitful in wide-ranging general knowledge, it has hitherto found only limited attention in wider circles. Even the few researchers who occupy themselves intensively with it, have only exploited a small part of this inexhaustible treasure house. Especially that part of their physiology, which interests us particularly here, the cell psyche of the radiants, their primitive “feeling and willing”, is so far hardly acknowledged. I myself treat it as a quite special favour of destiny that this “new world of microscopic life” became known to me more than sixty years ago, and that I could devote fully thirty years to its intensive study.

The strong specialisation of scientific research, which the new discoveries of the second half of the nineteenth century have led to, has produced in zoology a fragmentation into many individual branches. In the same way, as with insect science for entomologists and bird science for ornithologists, we single out a research speciality, we have distinguished the science of protists as a speciality (1866)—the natural history of single-cell life forms, and among these specialities is *radiotics*.

Psychomatics of Radiolaria

I have mentioned in my “General Natural History of the Radiolaria” (1887, para. 224) the general organic sensitivity, which the cell psyche of the Radiolaria shares with all protists, their abilities to distinguish various stimuli: 1. Pressure, 2. Heat, 3. Light, 4. Chemical composition of sea-water. This was in an appendix to the treatment, which I had laid out 25 years earlier in the first monograph—“The reaction to these stimuli, corresponding to the sensations of pain or pleasure, which they call forth, expresses itself reflexively in the different modes of motion of the protoplasm: alteration of the currents in the juice, contraction of the central capsule, alterations of size, place and form of the pseudopodia as well as the kalymma-volume (through entry of water) etc.” As a particular function of sensation of the Radiolaria I have also put forward their highly developed “sense of hydrostatic equilibrium”, as well as the “plastic sense of distance” which, in the production of the regular lattice, and other regularly formed skeletal components, reacts to the applied pressure” (1887, p. 21). These two *psychomatic* phenomena are of great special significance for the mechanical explanation of the highly multiform shapes and thus of such high general interest (also for the comparison with the related sensitivities of crystals), that they deserve here a closer examination.

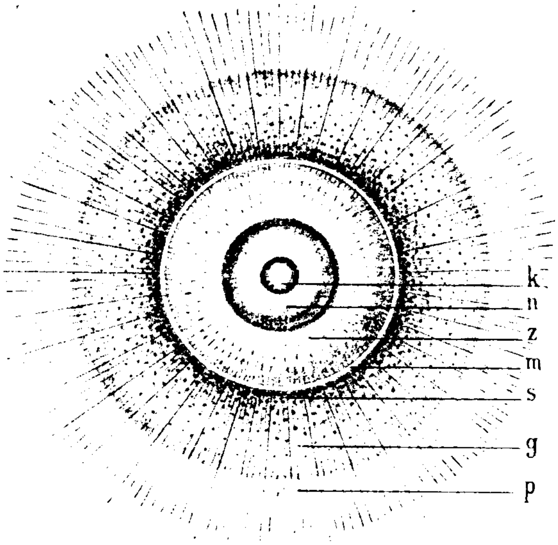

Fig. 25. Actissa radiata (Observed in 1887 living in Rhodes). The ancient form of the Radiolaria, from which all other forms of the class can be phyletically derived. The bare (not enclosed by a rigid shell) single cell body consists of concentric spheres; the cell nucleus (n) enclose a central nucleolus (k); the characteristic cell body (z) is separated by the solid membrane of the central capsule (m) from the soft enclosing gelatinous shell (kalymma, (g)). Numerous fine plasma threads (pseudopodia) come out of the cell body, traverse the membrane and radiate freely in all directions from the sarcode sheet (s).

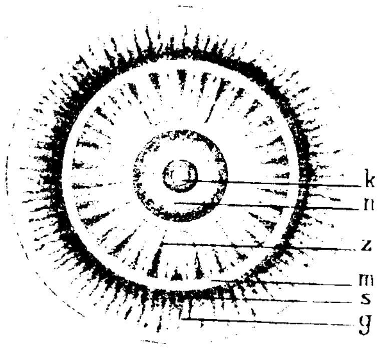

Fig. 26. Actissa radiata (the same form dead, killed and dyed by chromic acid). The pseudopodia radiating in all directions have their moving parts drawn back. The soft gelatinous shell (g) is strongly pulled together. Inside the central capsule the cytoplasm shows a clear radial structure.

Statotaxis (Sensitivity to equilibrium)

All Radiolaria live swimming in the sea and clearly have the greatest pleasure when, in a particular place, they can hold their single-celled body in equilibrium. They stretch out then in all directions, unchecked by other external hindrances, their pseudopodia which

Two sub-classes and four legions of radiants (Radiolaria).

I and II Legions: Porulosa (holotrypasta) Central capsule polyaxonic, without main opening, penetrated by numerous fine pores.	III and IV Legions: Osculosa (merotrypasta) Central capsule monoaxonic, with a main opening at the basal pole of the vertical main axis.
I. Legion: Spumellaria (Foam radiants = peripylea) Central capsule originally round, with central core: membrane penetrated by numerous equally distributed pores, out of which the plasma fibres emerge. Skeleton siliceous (often lacking) never *centrogen*. Biocrystal character regular. Figs. 27–29 (Plate C, Figs. 1–5 and 8).	III Legion: Nassellaria (Basket radiant = monpylea) Central capsule originally ovoid, with eccentric core. Osculum (basal main opening) with one pore field (porochora) from the sieve cover of which emerges a bundle of plasma fibres. Skeleton siliceous (rarely lacking) never *centrogen*. Biocrystal character monoaxial. Fig. 37 (and Plate C, Figs. 6, 9 and 10).
II. Legion: Acantharia (Star radiants = actipylea) Central capsule originally round, with eccentric core. Membrane penetrated by numerous regularly arranged pores out of which the plasma fibres emerge. Skeleton of acanthine or celestine, sometimes *centrogen (*radiating from a centre) Biocrystal character tetragonal. Figs. 31–36.	IV. Legion: Phaeodaria (Tube radiants = cannopylea) Central capsule spheroidal with central core. Osculum (basal main opening) with a star cover (astropyle) out of the mouth (canna) of which a plasma stream emerges. Skeleton from carbonic silicate, never *centrogen.* Biocrystal character polymorphic. Figs. 38–39.

serve them as fine sense organs for warning and as adept catching organs for seizing their prey—the diatoms, peridines, flagellates, infusoria etc. Since these pseudopodia, as gelatinous and variable extensions of the cytoplasm cannot be recognised as having any further differentiation, we can find out directly only a little about their sense functions. We can, however, deduce more indirectly from the highly multiform and complicated build of their skeletons, which are constructed by the pseudopodia. The conspicuous similarity to crystals, which these silica skeletons and celestine[1] skeletons show in their delicate regular building, directs us to the assumption that also here as for the crystals similar molecular forces (unknown directional forces—the *molethyn*) are active.

Actissa, the basic form of Radiolarian is, out of all the five thousand of the richly varied forms which can be derived phylogenetically, a simple spherical cell. As for all other Rhizopoda of this class, this single-celled organism is distinguished in that a firm membrane separates the inner mass, the central capsule, from the external gelatinous shell, the kalymma. In the middle of the endoplasm which fills the capsule, lies the spherical cell core. The exoplasm, which covers the outside of the capsule as a *sarcomatrix*, radiates in all directions innumerable fine fibres, the pseudopodia, which go through the gelatinous shell of the kalymma and extend out into the sea-water as organelles of sensation and nourishment.

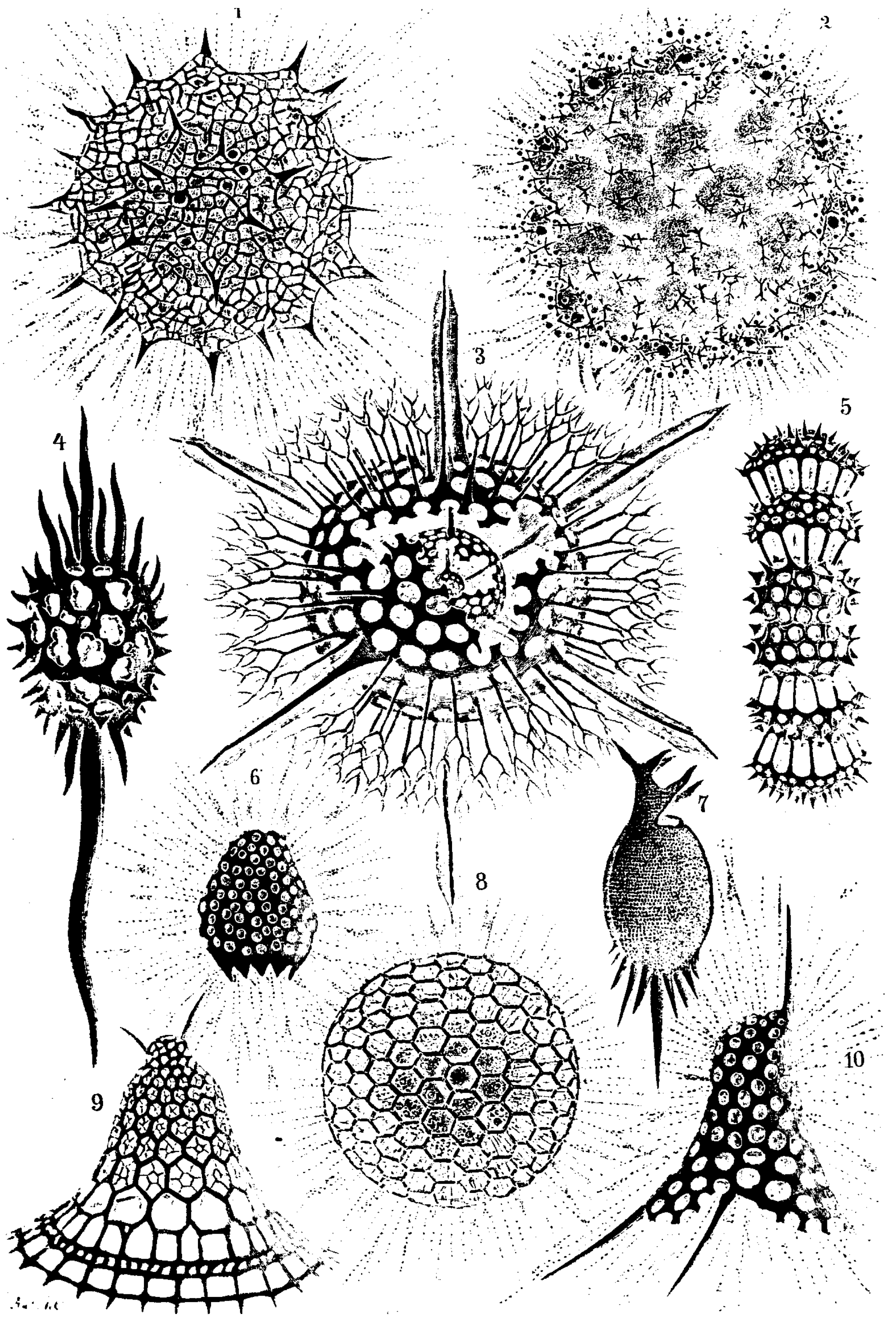

Plate C.

The Actissa, next most common and just as interesting, is the widely dispersed fresh-water heliozoan form Actino-sphaerium, on the cellular life of which the recent exact observations and experiments of Richard Hertwig have given us important information. Its spherical cell body also shows the partition into two different parts, the inner core-containing endoplasm and the outer foamy and core-free exoplasm. The characteristic membrane is still lacking here, which as “central capsule” separates the two parts and which shows the most important characteristic of the Radiolaria. This capsule membrane is, in the first class, the Porulosa (= Holotrypasta) perforated by innumerable fine pores, which permit direct connection between the inner and the outer plasma bodies. In the second sub-class, the Osculosa (= Merotrypasta) only a larger opening (osculum) in the membrane is present. A bundle of pseudopodia stretch out through this.

As for the Chroococcus among the probionts, the Actissa deserves among the Radiolaria, as the simplest prototype, quite special attention. For these primitive “ancient forms”, which exhibit, not only the ideal original picture of a whole class, rich in forms, but also the real reproduction of their general hypothetical family form, show us the

Explanation of Plate C.
This plate C shows together ten different Radiolaria, much magnified. They are members of three *legions*: Figs. 1–5 and 8; Spumellaria, Figs. 6, 9 and 10; Nassellaria and Fig. 7; Phäodaria.

Fig. 1. Rhizosphaera leptomita (Sphaeroidae). The round lattice shell is (if treated geometrically) a sub-regular endo-spherical polyhedron, from the edges of which pointed radial spicules protrude. Through the meshes of its irregular silica network radiate numerous fine plasma threads (pseudopodia) which emerge from the central capsule.

Fig. 2. Sphaerozoum ovodimare (Sphaeroidae). This round coenobium is viewed in meridional section. On its surface twelve lenticular flattened central capsules are visible. Between them are small bright points, the single-celled yellow protphytes (Zooxanthellae) which live in symbiosis with the Radiolaria. Fine crystalline silica needles (spicules as in Fig. 40) are distributed through the assembly of cells. The round bubbles in the gelatinous mass of the spherical coenobium are alveoli filled with sea-water.

Fig. 3. Actinomma drymodes (Sphaeroidae). The latticed silica shell is composed of three concentric spheres which are tied together by six strong radial rods. These lie in three mutually perpendicular directions, corresponding to the three axes of the cubic system. From the outside of the outer lattice shell, (the youngest and largest), emerge numerous hair-like radial silica spicules, which are forked at their outer ends.

Fig. 4. Lithomespilus flammabundus (Prunoidea). The egg-shaped uniaxial lattice shell carries at the lower pole of the axis one strong silica spike and several weaker spicules.

Fig. 5. Ommatocampe nereides (Prunoidea). The silica shell is composed of several members, six hemispherical chambers, three up and three down, attached to the original central lattice sphere.

Fig. 6. Carpocanium diadema (Nassellaria). The ovoid lattice shell, whose lower opening carries a wreath of teeth, radiates pseudopodia in all directions.

Fig. 7. Challengeron willemoesi (Phacodaria). The ovoid lattice shell shows an exceptionally fine diatom structure (as Fig. 49) and is armed above with five-pronged tooth at the mouth opening.

Fig. 8. Heliosphera inermis (Sphaeroidae). The simple spherical silica shell consists of a network of regular hexagonal meshes[2]. From the included central capsule numerous hair-like plasma threads radiate, emerging from the endo-spherical polyhedron.

Fig. 9. Clathrocyclas jonis (Nassellaria). The bell-shaped lattice shell carries on top two peak spicules and under the bell opening a delicate mesh ring with a wreath of spicules.

Fig. 10. Dictyophimus tripus (Nassellaria). The helmet-shaped lattice shell is supported by four radial silica spicules, which run together inside it (as the face normals of a tetrahedron). The three lower correspond to the edges of three-sided pyramid while the fourth crowns its peak. Numerous hair-like pseudopodia radiate from the enclosed central capsule.

phyletic path, along which the wonderfully unique forms have evolved in the course of more than a hundred million years. Fossil Radiolaria, and in fact predominantly the silica skeletons of Spumellaria of the regular crystal systems, are frequently embedded in sedimentary layers of more recent and of older periods, and recently have been found in the oldest deposits of the Cambrian and Pre-Cambrian systems. From comparative morphological analysis, and from the phyletic interpretation of their bio-crystal forms, we can draw conclusions about the historic evolution of the simple spherical cell bodies, whose fluid radiations have built these geometrically constructed skeletons, and on the *psychomatic* activity of their “feeling and willing cell psyche”.

Especially instructive in this connection are the older and more simply built Porulosa (Spumelaria and Acantharia). The younger Osculosae (Nassellaria and Phaedaria) show a complicated organisation. The central capsule assumes here a uniaxial form, while the Porulosae mostly keep the essential equiaxial spherical form.

The psyche of the Spumellaria (Peripylea)

This first legion of the Radiolaria includes the most primitive and the oldest forms, at the root of the whole tree of spherical skeleton-less Actissa, from which all other forms of the “radiants”, can be traced back both morphologically and phylogenetically. Most Spumellaria build as organelles, protective of their central capsule, an external lattice shell, or several shells, concentrically connected by radial rods. When these rods do not project outside, the original labile or indifferent sphericity of the body is maintained (Plate C, Figs. 1 and 8). When alternatively the radial spicules project externally, then the body has different diameters in different directions. In the Stylospheridae and the Prunoideae two large spicules grow out in opposite directions and determine a vertical main axis, while the spherical central capsule often becomes ellipsoidal (Plate C, Figs. 4 and 5). For the Staurospheridae and Discoidea four large main spicules, standing in two mutually perpendicular horizontal axes, form a lens or disc with a correspondingly flattened central capsule (Fig. 27). In the Cubospheridae six equal large main spicules emerge, lying in three mutually perpendicular planes, as the three axes of the regular (cubic) crystal system (Plate C, Fig. 3). In the Larcoidae, the same three perpendicular axes are moulded in the complicatedly constructed lenticular elliptical shell, but they are of different lengths in the three directions (as for the sterro-crystals of the orthorhombic system). The multiple modifications, which these constructions of the simple spherical shells and their external appendages (protective organs and suspensory apparatus) show in the different families of Spumellaria, are often connected with significant changes of position of the free floating single cell bodies and are determined by changes in their hydrostatic equilibrium[3]. Three ray forms are very numerous among the disc-shaped Discoidea, where three equal arms at equal angles of 120° emerge from the edge of the shell and develop in their mid-planes (Fig. 28). Other discs are regularly six-rayed, like certain snow crystals (Fig. 29). If one compares critically these mathematically regular forms of the Discoidea with the related forms of snow crystals (Plate B), one can discover no difference of principle in the construction of the molecule and also in the plastic action of their *molethyn* (of the “molecular directional forces”). The hexagonally radiating discs (Fig. 29) correspond to the holohedral, and the tri-radial forms (Fig. 28) to the hemihedral snow crystals of the hexagonal system.

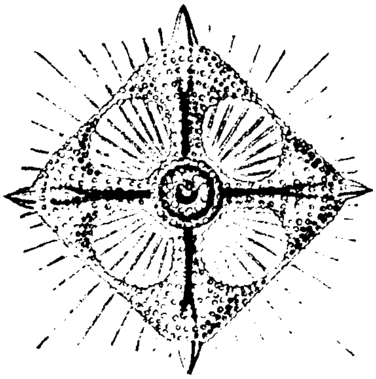

Fig. 27

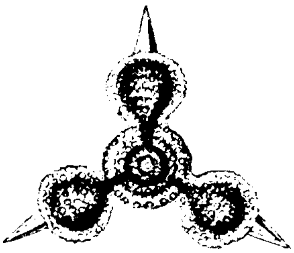

Fig. 28

Fig. 29

Fig. 27. Stephanastrum quadratum (Spumellaria). A regular four-rayed disc, with four crossing arms, the wings of which join together at the rim.
Fig. 28. Rhopalastrum trispinosum (Spumellaria). A regular three-rayed disc, with three bulbous arms tipped with daggers.
Fig. 29. Hexinastrum geryonidum (Spumellaria). A regular six-rayed disc with six wing-like arms connected by webs.

The psyche of the Acantharia (Actipylea)

This second legion of the Radiolaria, of particular interest for the *psychomatics* of the protists take, like the Spumellaria, their emergence from the simple spherical cells of the Actissa. They are distinguished, however, from the latter, as from all other groups of this class, by more conspicuous ideosyncracies. Among these the skeleton is *perigen* (generated at the periphery), it appears essentially outside the central capsule and never goes outwards from the centre of the cell sphere. Oppositely, the skeletons of all Acantharia consist essentially of many radial spicules, which go outwards from the centre of the sphere; it is *centrogen*, as a sphero-crystal. Because of this, the cell nucleus, which

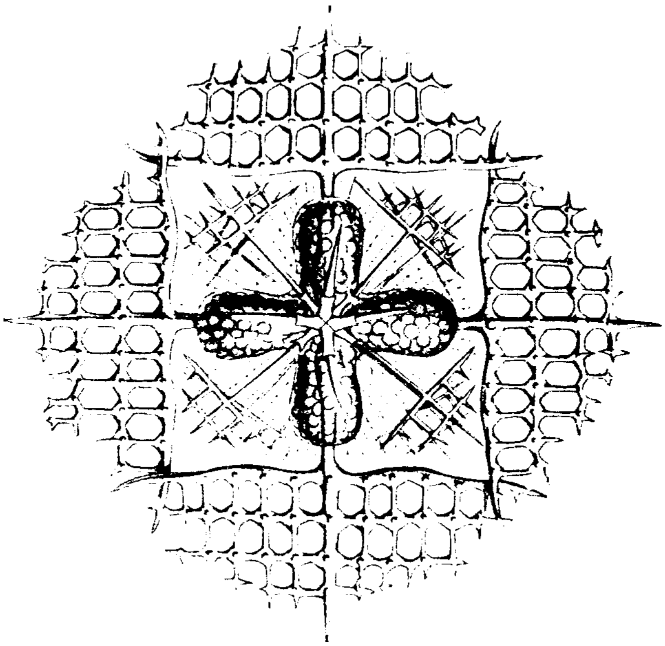

Fig. 30. Lithoptera dodecaptera (Acantharia). An acanthometran, whose 20 radial spikes are divided according to the icosacanth law of Johannes Müller into five parallel rings each of four crossing spicules. The four main equatorial spicules are larger and carry at their ends broad latticed wings. The eight tropic (circle) spicules, weaker and alternating with the former, each carry smaller latticed wings. In the middle is the four-fold cross-shaped central capsule.

originally lay just in the middle, is displaced and lies eccentrically. A further difference resides in the chemical composition of the skeleton. Here this is not built of silica (as in the other three legions), but is either a unique organic substance (acanthin) or is celestine (strontium sulphate) or is a mixture of both. The pseudopodia radiate here from the central capsule, as in the Spumellaria, in very great numbers; but they are not without order, and are ordered in definite rows or tufts between the spicules (Fig. 31). The numerous pores, through which the pseudopodia stretch out, in the capsule membrane correspond to this, not equally divided, but limited to definite lines or net-like fields.

The phylogeny of the Acantharia demands a quite special interest, in both its morphological and its psychological connections. The cell psyche here reveals such a high level of fine sensitivity (especially of plastic feeling for distance) and such a determined activity of will in the building of its skeleton, that an intense *psychomatic* for this single cell protist can alone supply information for the solution of many general questions. There is immediately here the external similarity of the organism with rigid crystals, and the inner correspondence of the *molethyn* (or "molecular directing force") with that of liquid crystals is so obvious that a further intensive study promises still more interesting fruits.

The legion of the Acantharia, rich in forms, includes twelve different families which can be divided into two orders, the acanthometres and the acanthofracts. For the first the

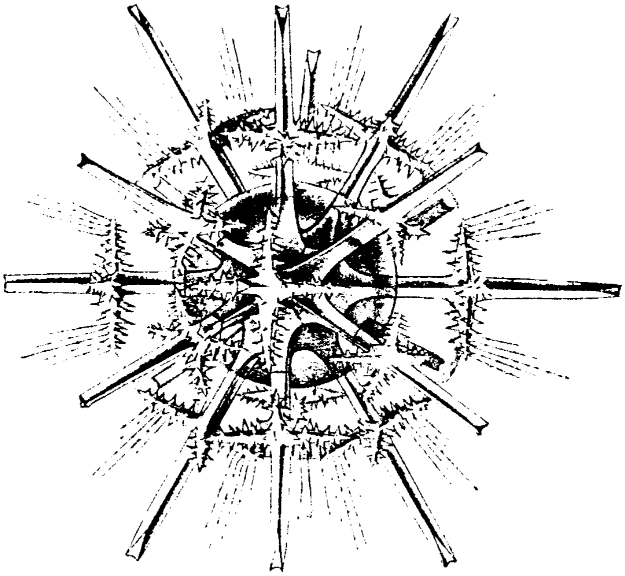

Fig. 31. Xipacantha spinulosa (Acantharia). An acanthmetran with 20 radial spicules which carry each a cross with four thorny tangential arms at the spherical surface of the gelatinous shell (kalymma). The equatorial plane is perpendicular to the paper in this figure. The axis without spicules (North-South) stands vertically.

skeleton is built from bare radial spicules which radiate from the central capsule (Figs. 30 and 31). For the latter there is also an external lattice shell, which is built from tangential extensions of the radial rodlets and encloses and protects the capsule.

Actinelius can be treated as a general family form for all Acantharia, a star with numerous indeterminately ordered rays which go out from the midpoint of the spherical capsule. It could be derived, either from Actissa or from Actinosphaerium, by hardening of a part of the centrifugal pseudopodia. While for these lowest Astrolophidae, which show the radial structure of an inorganic sphero-crystal, the number and ordering of the radial rods is quite undetermined they become, in contrast to the Acanthonidae, and especially to the great majority of the Acantharia, which have a remarkable, quite determinate order. This had been already discovered by the founder of the whole class, Johannes Müller and was named by me after him as the "Müller law of position" (or also the "*icosacanth* law"[4])[5]. Always here essentially twenty radial spicules are built out of the floating single-cell body, which is divided into five belts by each four rays. For understanding this remarkable, strongly inherited ordering the comparison with the Earth's sphere will serve. On the surface of this five parallel circles are drawn, the horizontal equator and on each side two tropical circles and two polar circles. If one now regards the globe from above (from the North pole), then its perpendicularly situated axes are without spicules. Oppositely, there lie in the plane of the equator four spicules in two mutually perpendicular cross-sections (these are often larger and formed differently to the sixteen others). On each side of the equatorial plane stand four spicules, whose points lie in the tropical circles, and further upwards and downwards, four more spicules each, whose points lie in the polar circles.

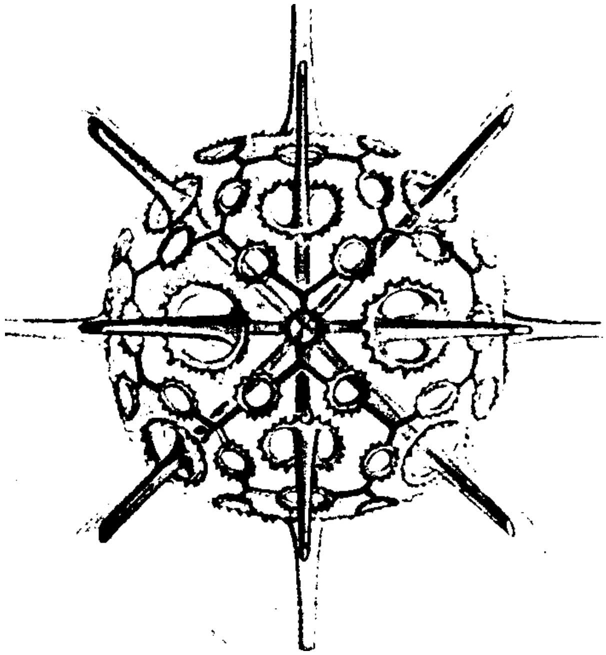

Fig. 32. Dorataspis typica (Acantharia Diporaspida). An acanthophractan, the spherical shell of which is built up of the simultaneous crossing of 20 radial spicules two by two; each of the 20 tablets is pierced by two aspinal pores. A coronal pore lies in the seam between each pair of tablets.

These five parallels alternate regularly with each other so that the four equatorial and the eight polar spicules lie in the same perpendicular meridian planes, which cross at right angles. Oppositely lie the eight tropical spicules in two meridian planes which cross at right-angles and which intersect the former at angles of 45°.

Acanthonidae

The Acanthometria with twenty radial spicules, which are disposed in regular geometrical positions according to the constant *icosacanth* law can be put into the sub-order of the Acanthonidae. They offer in their multiform development a large number of remarkable phenomena, which are of high interest both in their morphological connections for crystallography and for geometry and in their physiological connections for psychology and biogenesis (Fig. 31). The group of the Acanthonidae can be divided into three families. In the first and oldest family, the Astrolonchidea, all twenty spicules are of equal size (Fig. 31). In the second family, the Quadrilonchidea, the four equatorial spicules are larger and often differently formed from the sixteen others (Fig. 30). In these two families the equatorial plane is horizontal and has the basic form of a square. Their bio-crystal corresponds to a *sterro-crystal* of the tetragonal system. On the other hand the mid-plane stands vertically in the third family, the Amphilonchidae (Chall. Pl. 132); here two oppositely placed spicules much bigger than the eighteen others, and sometimes these two

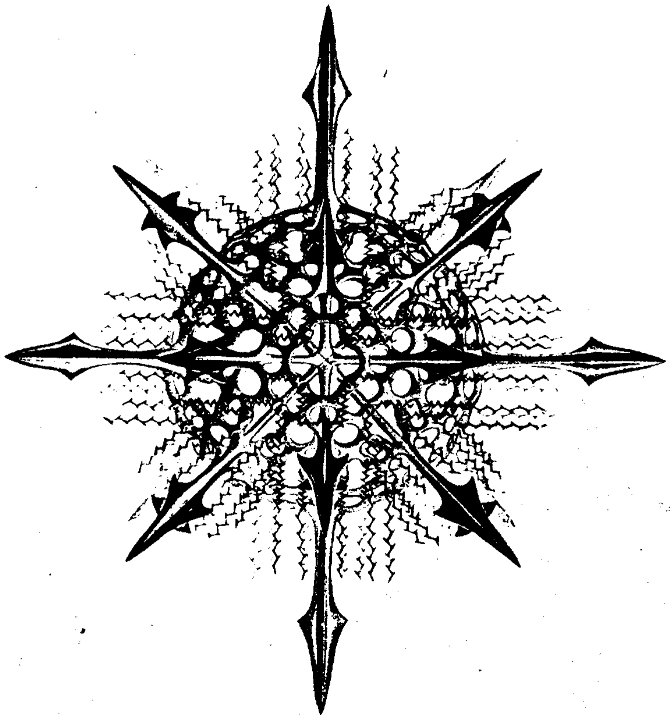

Fig. 33. Lychnaspis miranda (Acantharia Tesseraspida). An acanthophractan, whose spherical lattice shell is built of cross-shaped intersections of 20 four-edged (and at the ends spear-shaped) radial spicules; each of the 20 tangential tablets is pierced by four aspinal pores. There is a coronal pore at each seam where two tablets meet. Numerous delicate, zig-zag associated spicules grow out from the outer convex surface of the 20 lattice tablets. The direction of these is not radial but parallel to the main spicules, out of the edge of the tablets of which the small spicules grow. (This illustrates the operation of the plastic feeling for distance.)

main spicules are very different from each other in size and weight (Amphibelone). Here there can be no doubt that the single cell body has left its original place and has rotated by 90°. This is also indicated by the corresponding alteration in the shape of the spindle-shaped central capsule, the lower half of which is much thicker and heavier than the lower.

Acanthofracta (Challenger-Radiolaria 1887, plates 130–140)

The externally constructed lattice shell, the possession of which distinguishes the Acanthophracta from the Acanthometrae, is in many respects as rich a source for organic morphology and physiology as for inorganic crystallography and *psychomatics*. Originally a simple lattice sphere, which surrounds and protects the concentric spherical central capsule (Spherophracta), it has developed in different directions as a most rare armour. In the Belonaspidae the lattice shell becomes ellipsoidal and two opposite equatorial spicules grow much more strongly than the eighteen others. Here the lengthened *hydrotomic* axes are again perpendicular (as for the Amphilonchidae). For the Hexalaspidae the lenticular

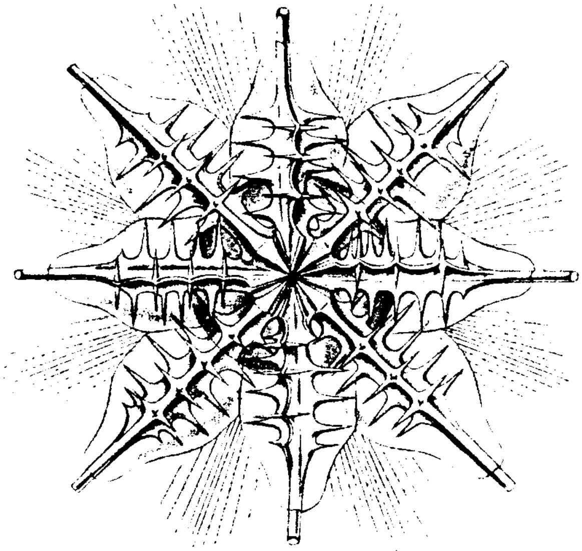

Fig. 34. Pristacantha polyodon (Acantharia). An Acanthometra with 20 radial spicules, of which only eight are drawn. The basal parts of the spicules are enclosed by spherical extensions of the gelatinous shell and carry four leaves, each of which carries two rows of parallel teeth.

flattened shell takes the form of a six-rayed star in which the six larger spicules (two oppositely equatorial and four polar, lying in the same "*hydrotomic*" meridian plane) become much stronger than the fourteen others (often built backwards) (Fig. 35). In the Diploconidae the shell is finally changed into a sand-glass or a double ninepin, and the basal invagination of the two *hypertrophic* equatorial spicules (in the *hydrotomic* meridian plane) are excessively developed, the other eighteen spicules are built backwards (Fig. 36). This very remarkable metamorphosis, the appearance of a sand-glass out of a simple radiating star, is shown in plates 130 to 140 of the Challenger Radiolaria (1887) in many examples.

The lattice shell of the Acanthofracts results from the star of the Acanthonidae because, on the surface of the spherical kalymma, in a tangential direction from the twenty radial spicules (perpendicular to their axes), oblique extensions grow out and branch. In the Diporaspidae (Fig. 32) two opposed apophysea emerge from each spicule, so that by their growth, altogether forty primary pores for aspiration result. Oppositely for the Tessaraspidae, (Fig. 33) four crossing *apophysae* grow out of each spicule, so that here through their growth, altogether eighty primary pores for aspiration are formed. The strongly geometrical symmetry is very remarkable, and is maintained both in the branching of the *apophysae* (at constant angles) and in the further building out of the right-angled lattice mesh in the tangential tablets formed in it. In this way that wonderfully complicated mansion of the Acanthophracts results, which in its mathematically correct structure, permits an exact promorphological analysis, and which has more similarity with many mineral crystals than with any other organic forms[6].

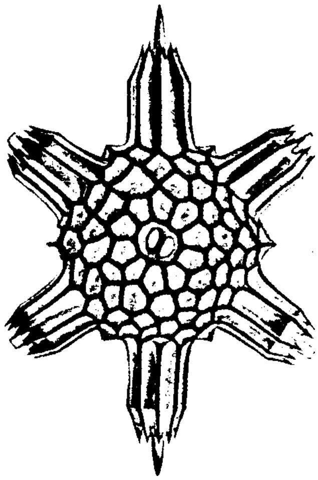

Fig. 35.

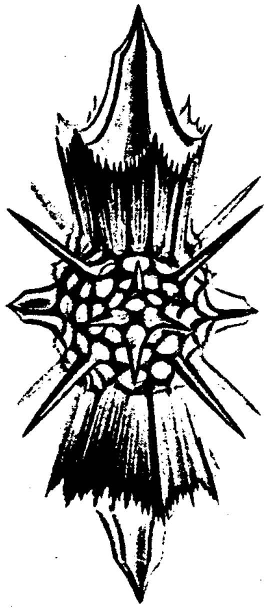

Fig. 36.

Fig. 35. Hexacolpus nivalis (Acantharia). An Acanthophractan the lenticular lattice shell of which is made up of 20 radial spicules (as in Doratapis, Fig.1). Fourteen of the spicules are small and rudimentary, not extending beyond the honeycomb of the external face of the shell. The six other radial spicules lie in the equatorial plane of the lens, extend out at the perimeter and are surrounded by strong parallel ribbed spike invaginations.

Fig. 36. Diploconus hexaphyllus (Acantharia). An Acanthophractan, whose shell takes the shape of a double ninepin through the extra development of two oppositely situated spikes and their basal invaginations. The other 18 spicules are rudimentary.

Protacanthea and Paracanthea

For very many acanthophracts very numerous fine needle spikes or spicules (*paracanthi*) grow out of the surface of the spherical lattice shell near to the original twenty main spicules (*protacanthi*). These are never directed radially, but exactly parallel to the main spicules. Since the latter are always opposite to each other all other associated spines (often several hundred or a thousand), run parallel to four different regularly divided and mathematically determined axes of the spherical lattice shell from the enclosed central capsule (Fig. 33). This conspicuous and recurrent positioning is only to be explained by the plastic feeling for distance of the pseudopodia, which divide the skeleton part, and by the *mnemes* of the plasma, which transmit these *psychomatic aestheses* by heredity. Since the twenty main spines in the centre of the capsule are mostly pressed together (rarely grown into one), they cannot easily be isolated. Each vertical single main spine exhibits then the form of a delicate candelabra, the middle of which carries a horizontal lattice plate with two opposite or four cruciform pores for aspiration. On the edge of this numerous associated fine spines stretch out perpendicularly. They surround the central main spine in order like a "birthday cake" on which the many small candles (giving the number of the years) stand round the stronger central candle (the so-called "life-light"). (See Challenger 1887, plates 137–138—"Art Forms in Nature", table 41.) Also for many Acanthidae, whose twenty rays carry at the base a four-winged leafy cross, there are teeth or near-spines, which go out perpendicularly from the leaves, directed parallel to the axes (Fig. 35).

The relationship of these and other crystal-like structures is particularly interesting in connection with the *molethyn*, that secret "molecular directional force", to the *psychomatic* meaning of which we have drawn attention by impartial comparison with the laws of crystallisation. In many spherical Doraspidae as well as in the large ellipsoidal Belonaspidae, there are in each of the twenty tangential lattice plates numerous (often several thousand) right-angled holes, and near two or four primary *aspinal* pores, many secondary *coronal* pores. Where now the lattice plates, each of which is independently oriented with respect to its main spicule, come together in the shell surface, there stand related figures, as in the crystallisation of ammonium chloride and other salts, whose "crystal skeletons" grow into each other on being pressed together (Figs. 1–3).

***Psychomatic* inheritance**

The comparative morphology of the Acantharidae, of which 400 different species have recently been described, leaves no doubt that the multiform, and at times very complicated forms, all are produced from a general ancient form—from a single round cell (actinelius), from the midpoint of which numerous fine rays emerge, as in a sphero-crystal. A long chain of connected transitional forms lead from this astrolophide to the Acanthonidae (with twenty spines regularly distributed in five parallel circles[7]). Initially these radii are simple, then they form oblique extensions (Fig. 31) and these go together to build a round lattice shell (Fig. 33). Later they change, in the Hexalapidae the sphere becomes a lenticular sheet (Fig. 35); fourteen spines become rudimentary; the six remaining become so much stronger that they emerge at the edge of the lens and build a six-rayed star, like a snow-flake (Fig. 35). Finally, at the youngest stage of phyletic development, there remain of these six spines only two opposite spines, exceptionally developed, while the eighteen others atrophy and completely or largely disappear (Fig. 36). However, the basal spine matrix of these two giant spines develops so much that it builds a whole new, very remarkable, shell form, a double sphere ("hourglass or double corset")[8].

Phylogeny of the Acantharia

The coherent chain of phyletic evolutionary steps, which are present in the multiform legion of the Acantharia still living today near one another, permits us to make not only their monophyletic derivation from Actinelius as a general ancestor; but it furnishes also fine evidences for the basic biogenetic law[9], the validity of which for the single cell protists is often doubted. The historical appearance of such a complicated crystal-like structure as for Lychnaspis (Fig. 33) repeats itself today in its individual evolution. For its ontogenesis shows, that at first twenty simple radii (following Müllers law) are formed. They then branch out (Fig. 31); their oblique extensions come together at the surface of the round kalymma to make a lattice shell, and eventually the hair-like neighbouring spines grow out of the surface, exactly parallel to the main spines (Fig. 33). This ontogenetic repetition of the long phylogenetic process, which has evolved in the course of many million years, is only understandable from the concept of the “radiating psyche”, from the *psychomatic* concept of its plastic activity (*mneme*).

The psyche of the Nasselaria (Monopylea)

The properties of formation and sensation in this third legion of the Radiolaria are certainly exceptionally multiform, but for our *psychomatics* are by far not as interesting as those of the two fore-mentioned legions, the Spumellaria and the Acantharia. While in these two groups of Porulosa numerous fine pseudopodia go out from the suspended sphere through the membrane in all directions, on the other hand the two legions of Osculosa (the Nassellaria and the Phaeodaria) are characterised by having the single-cell (usually egg-shaped) body showing from the beginning a vertical main axis, and in that, at their lower (basal) pole, there exists a single larger opening an *osculum*, out of which the plasma in the form of pseudopodia bundles emerges on one side. Consequently, the hydrostatic equilibrium of the Nassellaria is stable. The main axis of the central capsule, and thus the skeleton which surrounds it, is vertical, and always all *psychomatic* connections of the organism are determined by this characteristic structure of the basal opening, the *osculum*. This is always closed by a round sieve cover (*operculum porosum*) which the base of a unique ninepin of fibres sprouting from the inside of the capsule fashions. The pseudopodia emerge through numerous fine pores of the pore array (*porochora*) in the sieve cover.

The silica skeleton of the Nassellaria (Plate C, Figs. 6, 9 and 10) is composed of three different elements:

I. Of the sagittal ring, a simple silica ring or one with many branches, which lies vertical in the sagittal plane of the body. The central capsule surrounds it and is joined on at its basal pole;

II. Of the basal tripod, an oral tripod, composed of three divergent silica spines, which meet in the centre of the *porochora*, at the base of the vertical axis;

III. Of the *cephalis* or the lattice head, a simple egg-shaped or sub-spherical shell, which encloses the capsule and is connected to its main axis at the basal pole.

These three essential skeletal elements appear combined in the great majority of Nassellaria but also in many cases appear also singly or connected in pairs. From this arises the difficulty of the monophyletic derivation of their numerous forms of which more than 1600 kinds have been described. In single cases there are many interesting properties which throw light on their psyche and its mechanical functions. In general they are not of such significance as in the *Porulosa*. A very conspicuous form, Lithocubus, builds a cube-shaped shell, whose twelve edges (decorated with spiky protuberances) correspond exactly with the edges of a regular cube in the cubic crystal system (Fig. 37).

The psyche of the Phaeodaria (Cannopylea)

This fourth legion of the Radiolaria corresponds to the afore-mentioned third, in that the central capsule possesses only a large main aperture (*osculum*) at the basal pole of the vertical main axis. But the structure itself is quite different. The *osculum* is close by a radiating cover (*astropyle*), from the middle of which a tubular snout protrudes (probos-

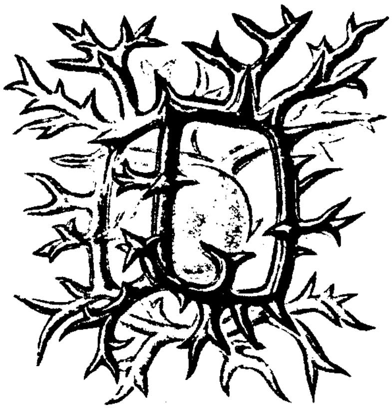

Fig. 37. Lithocubus astragalus (Nassellaria). The silica skeleton forms a regular cube with six square faces. Branching radial spicules grow out from the eight corners and from the 12 edges. The round central capsule oscillates about the middle.

cis); a stronger plasma stream comes out of this tube and broadens into a kalymma. A unique *phaeodium*, a voluminous, most brown or green pigment body fills up the greater part of the kalymma, especially in the neighbourhood of the *osculum*. Opposite this basal main opening there are often, but not always, two more small near openings (*parapylae*) visible on the upper or *aboral* dome of the spherical, or somewhat flattened central capsule. Most Phaedaria are true deep sea dwellers, and exceed the other three legions in their remarkable size (up to several centimetres). Many show rare forms of skeleton and particular complexity in the assembly of their parts. The substance itself is mostly a carbonic silicate, a characteristic compound of plasma and siliceous earth, only rarely pure silica. The rods which hold the latticework of the shell together, and the radial spicules, which go out from it, are often hollow tubes filled with jelly.

The marvel of the cell psyche

Through the many-sided differentiation of the single body and the formation of special organelles, the Phaeodaria appear to be “higher protists” in contrast to the other Radiolaria. On the same count their “cell psyche” is to be reckoned as a full psyche. It accomplishes here from time to time astonishing achievements in building the protective shell. Nevertheless the simplest forms here are also lattice-work spheres, which on the outer surfaces of the kalymma are separated. For Auloscena and Sagenoscena (Fig. 39) the network assembles the colossal lattice sphere, several millimetres in size, from regular triangular meshes, every six of which form a regular hexagon. On each hexagon is erected a regular six-sided pyramid, and on its apex (like a flagpole) stands a radial staff, which carries at its end a delicate crown or a wreath of thorn stars (“Spathillen”). The family of the Concharidae (mussel-radiants) is distinguished in that the extended (originally spherical) lattice shell is divided into two halves, which serve altogether like the two valves of a mussel shell. Sometimes also they are tied by a “locking band”. For the related Coelographidae there arise from the curvature of each valve a group of very ramified trees, whose hollow tubular stems are supplied with thousands of delicate spatulae and other appendages.

Regular Polyhedra

The polymorphic skeleton of the Phaeodaria stands out from the usual Radiolaria not only for the remarkable multiplicity and complexity of its silica products, but also for the geometric regularity of the lattice shell which is formed at the surface of the kalymma from the liquid plasma fibres. These pseudopodia radiate in greater number from the plasma stream, than emerge from the tube-like *osculum* of the central capsule ("*cannopylea*"). They diverge through the thick structure-less mass of jelly which encloses the central capsule, and form at its surface a *sarcode* net (*sarcodictyum*) in which the skeleton substance crystallises. This "bio-crystallisation" leads now mostly to the appearance of an "*endospheric* polyhedron". One family of the Phaedaria, the Circopiridae, is particularly distinguished in that here the rare forms of the regular or "Platonic" polyhedra, near to the usually sub-regular or irregular many-sided figures, appear. Geometry teaches us that only five different forms of really regular many-sided figures (in the strong stereometric sense) can exist.

I. The regular icosahedron (with twenty congruent equilateral triangular side faces) is clearly delineated in the Circoporidae circogonia icosaedra (Fig. 38) but also in certain Aulospheridae. The same basic geometrical form (like a crystal form) is possessed also by those spheroidal kinds whose spherical lattice shell carries twelve equal and equally separated radial spicules. The basal points of these spicules indicate the twelve corners of the regular icosahedron.

II. The regular dodecahedron (with twelve congruent, equilateral, five-cornered side faces: the pentagonal dodecahedron). This basic form is shown by the pollen grains of many plants (e.g. Fumaria spicata, Buchholzia maxima). It occurs for the Circoporidae circorrhegma dodecaedra, as well as for those Spheroidae and Acantharia from the lattice shells of which twenty equal and equally spaced radial spicules radiate and their basal points determine the twenty vertices of the regular dodecahedron.

III. The regular octahedron (with eight congruent equilateral triangular faces) repeats completely the geometrical form of the cubic crystal system in Circoporus octaedrus. In this remarkable variety the twelve edges of the octahedron bow out and the eight faces of the regular bio-crystal are flat or only slightly curved, and are tiled with a delicate regular hexagonal lattice-work. Oppositely, in another species of the same genus, the prolific Circoporus sexfuscus, the 12 edges are quite indefinite and the eight faces so strongly curved that the whole silica shell of the bio-crystal takes up the pure spherical shape. However, the six strong radial spicules, forked at their ends, which emerge equidistantly from the surface of the shell, indicate unambiguously the regular crystal form of the cubic system (as is also the case for Actinomma Plate C, Fig. 3). One can now suspect, that from the pure cubic crystal of C. octaedrus the spherical shell—the apparently "spherical crystal"—is secondarily derived from C. sexfuscus; but probably it is the other way round. The primary building plan is here, as for the Hexastylidae, the "axial cross" of the three coordinate axes, as an adaptation to the stable equilibrium of the floating plankton cell. This was also the judgment of Valentin Haecker, who in his work on the deep-sea Radiolaria of the Valdivia Expedition, has also illustrated these and other Circoporidae.

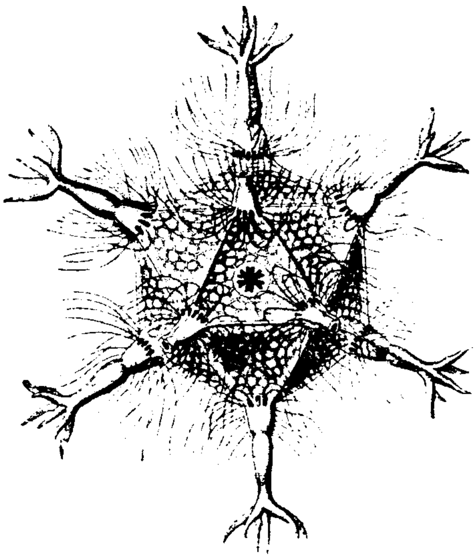

Fig. 38. Circogonia icosaedra (Phaeodaria). The silica shell has the geometrical form of a regular icosahedron, bounded by 20 equal, equilateral triangular faces. Radial spicules emerge from each of the twelve vertices and each of these carries a crown of five or six teeth.

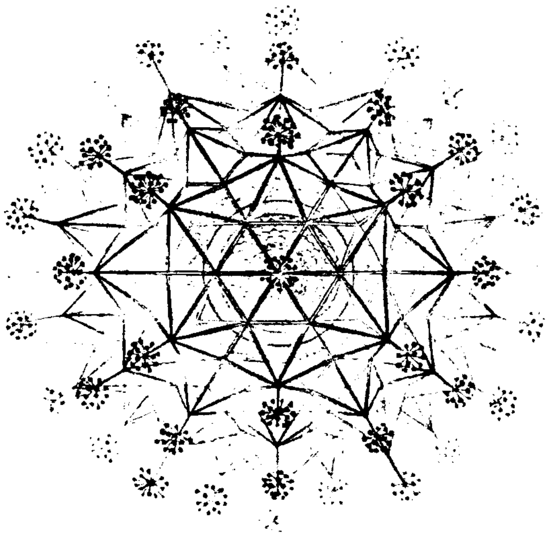

Fig. 39. Saganoscena stellata (Phaeodaria). The spherical central capsule is surrounded by a thick spherical gelatinous shell (kalymma). At its surface the numerous radial plasma threads exude a concentric lattice shell of branched construction. Each six hollow silica tubes form a regular hexagon, the basis of a six-sided pyramid, at the apex of which a radial rod is erected like the flagpole on a tent. The point of each pole carries a crown or a star formed of knobbed radial spicules.

IV. The regular hexahedron (with six congruent square side faces) occurs in the silica skeleton of different families of Radiolaria. In the Lithocubus (Fig. 37) the twelve edges of the lattice enclosure correspond completely to the edges of a geometrical cube. In many Astrospheridae, the inmost, the first-formed shell around the spherical capsule, is a cube from whose eight vertices eight radial spicules go out to the same distances. From the tangential branches of the same there results from growth a spherical concentric skin shell, which develops further on the outside a voluminous spongy interlacing. (Compare Octodendrum, Challenger Radiolaria, plate 18, figures 1–3.)

V. The regular tetrahedron, with four congruent, regular triangular side faces, appears as a crystal basic form in some primitive forms of Nassellaria: tetraplagia among the Plagonidae and tetraplecta among the Plektanidae. The whole skeleton consists here of four straight, mostly three-edged silica rodlets, which radiate from a common middle point at equal distances at equal angles to each other: they correspond exactly to the face-normals of a regular tetrahedron. Among the numerous forms of these Plektellaria derived from it, the cortinaform is particularly important, in it the central capsule rests below on a basal tripod, while the fourth ray develops above to a peak spicule. This same basic form of the regular four-rayed axial cross recurs also as an organelle in the silica spicules of many Beloidea among the Spumellaria. Out of it there develop the multiform three-ray and four-ray and six-ray forms of spiculae, which surround the central capsules of the many Spherozoidae and Thalassospheridae in great number as tangential protective shields (Figs. 40 and 41).

Crystalline spicule (Beloid skeletons)

Figures 40 and 41. Very remarkable crystal-like silica forms occur in the Spumellaria order of the Beloidea or “needle radiants”, both for the solitary Thalassospheridae (Fig. 40) as well as for the social Spherozoidea (Fig. 41 and Plate C, Fig. 2). These rigid silica structures (usually designated as “needles” or spicules) are extruded from the liquid pseudopodia outside the central capsule into the surrounding gelatinous shell (kalymma); sometimes they are simple cylindrical solid rods, sometimes they branch or at both poles separate into three divergent legs, which correspond to the face-normals of a regular tetrahedron. From these, simple or branched side-branches can again emerge at right angles, just as for many skeletons of *sterro-crystals* (Figs. 1, 2 and 9). Usually the needles lie in great number on the external faces of the central capsule, tangential to its spherical surface. In the coenobia of the social Beloidea they are also massively present in the jelly mass (kalymma) of the cell union, which holds the united cell capsule together (Plate C, Fig. 2),—In many social Spumellaria, for which the common kalymma contains large spherical vacuoles, there develops sometimes in the centre a special central alveola (Fig. 43); it forms a general firm supporting organ for the soft cell assembly.

The psyche of the diatoms

The diatoms furnish a very remarkable, and in many respects instructive, parallel to the cell psyche of the Radiolaria. As for the single celled animals (Protozoa), so here for the single cell plants (Protophyta), the formative plasma, richly endowed with sensation and movement, shows an extraordinary diversity in the production of the silica shell, which serves as protection for the delicate cell body. While the Radiolaria (of more than

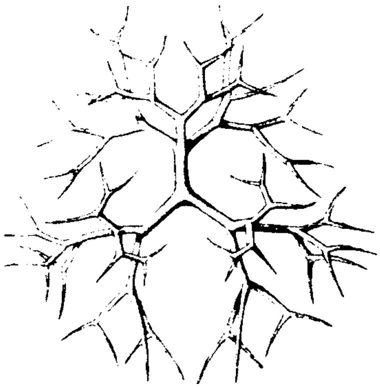

Fig. 40.

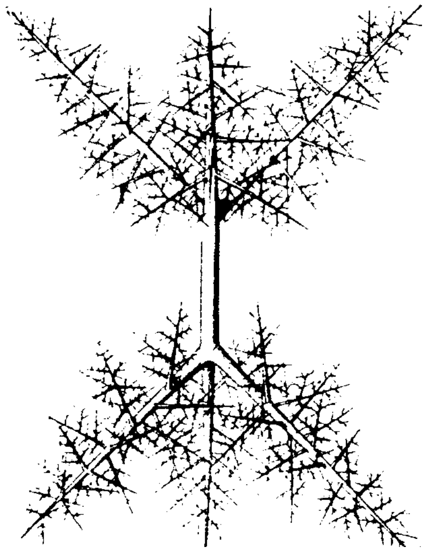

Fig. 41.

Fig. 40. Thalassoxanthium cervicorae (Spumellaria). A single cell three-branching crystalloidal silica body, whose three limbs meet at the same angle and repeatedly form forked branches.

Fig. 41. Sphaerozoum spinosissimum (Spumellaria). A single-celled silica body (biocrystal) whose cylindrical central stalk carries three divergent limbs at each end, corresponding to the axes of a regular tetrahedron. Each limb carries many branches decorated with thorns.

5000 kinds) live swimming in the sea, the diatoms, on the other hand (of hardly fewer kinds) are present copiously both in the sea and in fresh water, sometimes floating or moving actively (swimming or creeping) sometimes staying still. Their imperishable silica shells sink after the deaths of the cells to the bottom of the water and can, in the course of many millions of years, become so massively heaped up that they become thick rock and comprise whole mountain masses (polished sections). The physiological contradiction between the two classes of protists resides in this that the diatoms (as true plants) assimilate carbon and through synthesis from water, carbon dioxide and ammonia build new plasma. On the other hand the Radiolaria (as true plasmaphagous animals) no longer understand this chemical art, but must for their nourishment take up plasma from other organisms; among which the most significant role as a source of foodstuffs is played by the diatoms.

Diatom shells

It is very important in the comparison of diatoms with Radiolaria, and what sets them apart in so many connections, is the circumstance that their skeletons are built up of silica. From this is apparent the overwhelming similarity which their crystalline engraved shells

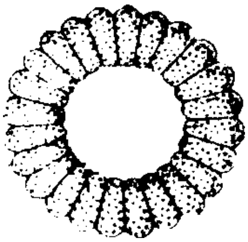

Fig. 42. Collosphaera primodialis (Spumellaria). A ring-form coenobium. The wreath-like cell colony is divided by radial partitions into wedge-shaped parts. This rare form of coenobium results from the chance growth at both ends of a cell colony. The fine points in the gelatinous mass are the single cells (individuals).

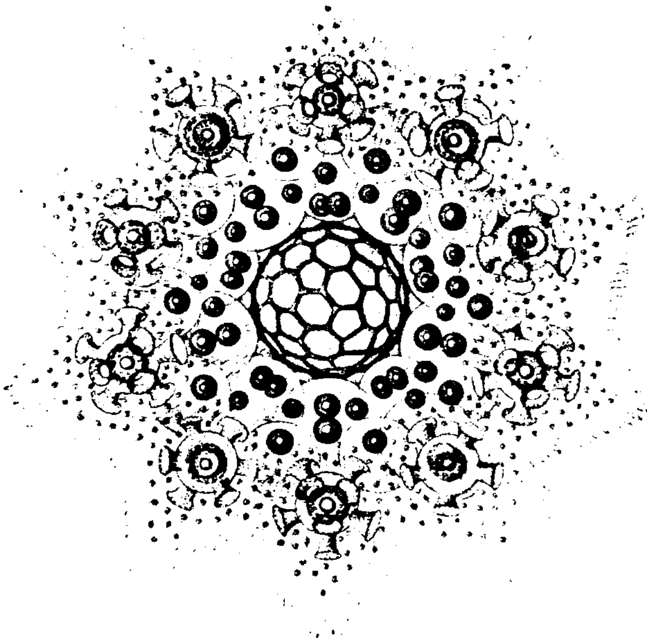

Fig. 43. Solenosphaera familiaris (Spumellaria). A cell coenobium, the gel mass (kalymma) of which contains many spherical water bubbles (vacuoles). In the middle lies a large bubble (central alveole), whose wall is thickened and surrounded by a plasma-net. The numerous single cells, which together make the coenobium, are naked in the inner part and are depicted in the course of multiplication by division. The larger and older cells at the surface have generated silica shells which carry horn-shaped extensions.

show in respect of fine structure (and also the corresponding molecular activity). The conspicuous regularity is especially remarkable, with which the lattice formation (*dictyosis*) repeats in both classes of protists. In the usual Navicula forms, the lattice-work of the solid silica shells is assembled with thousands of equal-sized and regular hexagonal meshes. This sculpture is so fine in many cases, that it is only visible with the strongest magnification and that these fine structures are used as test objects for the testing of microscope lenses[10]. Just the same characteristic hexagonal network is repeated in the shell structure of many Radiolaria, namely among the Challengeridae. Here as there, we can only explain by *psychomatic* concepts, through the assumption, that for the building of these bio-crystals, the plasma when compounded with silica activates a higher degree of sensation and will. The shell form of the diatoms in themselves is mostly simple. The original spherical form mostly becomes flattened to a disc, which sometimes is round (Fig. 45) and sometimes polyhedral (triangular, Fig. 44), four-rayed (Figs. 46 and 47) eight-rayed (Fig. 48). A most highly complicated symmetry of lattice structure is shown by the ten-rayed Auladiscus grevilleanus (Fig. 49). The silica shell has the form of a small box with a cover; for the propagation by division the two halves of the box separate, whereupon each half completes itself by the synthesis of a new half.

Dictyosis (lattice formation)

The silica shell of most Radiolaria has the structure of a fine lattice and is pierced by numerous holes, through which the pseudopodia can stretch out. At first the lattice work is mostly very fine and regular, built of hexagonal meshes of uniform size. Later these six-cornered holes often become round or irregular. The same regular hexagonal structure reappears also in the silica shells of most diatoms, those single-cell protophytes which show so many ecological relationships with the Radiolaria and often form their main nourishment. Both classes of protists resemble each other also in the fine structure of the silica armour, which is formed through the combined activity of the organic plasma and the inorganic silica. The overall regularity of their dictyosis permits the question to be put as to whether both classes of silica-shelled protists rest upon similar bio-crystallisation

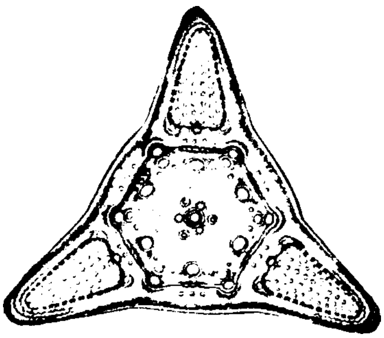

Fig. 44.

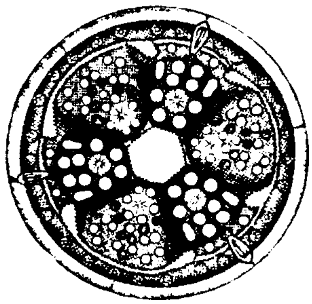

Fig. 45.

Fig. 44. Triceratium digitale. The silica shell is a regular triangular disc; in the middle is a regular hexagon. It is like a hemihedral hexagonal snowflake (cf. Plate B, Figs. 1–8).

Fig. 45. Actinoptychus constellatus. A silica shell like a circular pill-box; in the middle of the cover is a regular hexagon. From the corners of the hexagon radiate six radial beams; these separate three broad fine-mesh fields from three fields with coarser mesh (like a hexagonal snowflake as Plate B).

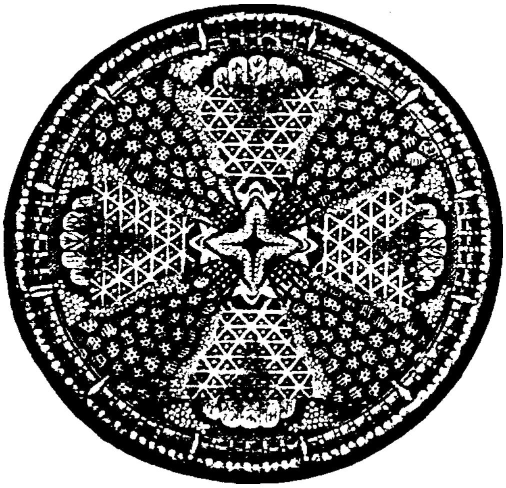

Fig. 46.

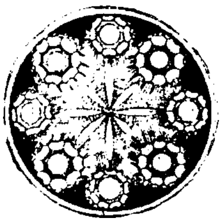

Fig. 47.

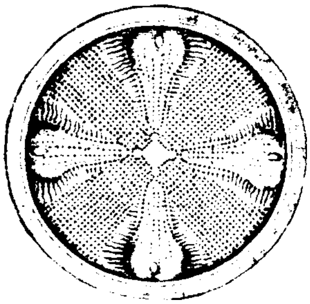

Fig. 48.

Fig. 46. Actinoptychus heliopelta. The silica shell is a round pill-box, the cover of which shows a regular four-rayed cross. Four broad radial fields alternate with four diminishing inter-radial fields. The single-cell organism resembles exactly the typical basic form of the regular four-rayed medusa (in the centre is the cross-shaped mouth).

Fig. 47. Auliscus craterifer. The silica shell is an eight-fold disc; at the perimeter four brighter per-radial octagons alternate with four darker inter-radials.

Fig. 48. Aulacodiscus mammosus. The silica shell is a round pill-box with a regular four-fold symmetry (tetragon2al crystal system), A regular cross is formed from four small wedges which separate four wider fields with very fine lattices.

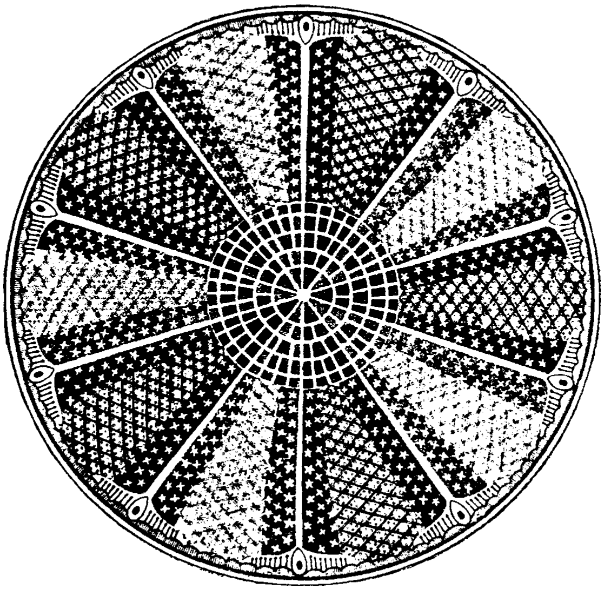

Fig. 49. Aulacodiscus grevilleanus. The silica shell is a round pill-box, the lid of which shows in the middle a system of concentric rings and at the periphery a star with ten bright rays. Through these ten equal-limbed three-cornered radial fields separate, five brighter alternating with five darker. The hollows or pores of the lattice-work are extraordinarily fine, star-shaped, and ordered in crossing and alternating rows.

processes. Both in the fine sensitivity of their delicate cell psyche, and in the firm will, with which they, in the building of their wonderful lattice shelters, the molecular motion is organised into definite directions, lead directly to the comparison with the crystallisation of the *sterro-crystals*. The “homology of the *molethyn*”—the same regularity in the working of the “molecular ordering forces” in those organic and these inorganic crystal structures is most remarkable. Below in the fourth chapter we will have something to say more about the *psychomatic* explanation of these facts, in comparison with the “space-lattice” of the *sterro*-crystals.

Notes

1. Strontium sulphate.
2. 12 pentagonal meshes would be expected among the hexagons!
3. *Haeckel's note*: Compare here tables 1–50 of the "Challenger radiolaria" and tables 11, 51 and 91 of "Kunstformen der Natur".
4. This does not imply icosahedral symmetry. The 20 is made up of 8 + 12 with cubic symmetry.
5. For a modern account see: J. R. Wilcock, C. C. Perry, R. J. P. Williams and R. F. C. Mantoura, "Crystallographic and morphological studies of the celestite skeleton of the Acantharian species *Phyllostaurus siculus*". Proc. R. Soc. Lond. **B 233**, 393–405 (1988) and *ibid*. two subsequent papers.
6. *Haeckel's note*: See for this the twelve tables in the third part of the German "Monographie der Radiolarien": Acantharien oder Actipyleen-Radiolarien (Berlin, Reimer, 1888). The same forms are to be found in tables 129–140 of the English Challenger Radiolaria (1887). The notable treatment of these is shown impressively in a long authoritative description. A small selection of the most conspicuous forms is given in tables 21 and 41 of my "Art Forms in Nature".
7. Parallels of latitude.
8. *Haeckel's note*: I have shown such forms already in my "Natural History of Creation" (11th. Ed. 1909, plate 15, figure 6; plate 16, figure 11). Other examples are exhibited in the "Art Forms in Nature" plate 21, figure 41.
9. Haeckel's "ontogeny recapitulates phylogeny".
10. It is also remarkable that the early optical microscopists had discovered that inclining the illumination of a parallel illuminating beam (coming from below the microscope table) could double the resolving power (see the 9th. Ed. of the Encyclopaedia Britannica, 1910). This application of Ernst Abbe's diffraction theory of the lens was re-discovered very much later by electron microscopists in connection with the optical transfer function developed by H. H. Hopkins.