THE UNIVERSITY OF MICHIGAN
INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

THE MAGIC CARPET: WATER-FLOATED MAGNETIZED BALLS FORM STANDING WAVES WHEN DRIVEN BY A-C MAGNETIC FIELD

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SUMMARY

Thousands of magnetized balls, floating free on water and activated by an a-c magnetic field, form a dynamic, ever-changing raft. With the raft confined within a square frame, the "magic carpet" appears: a checkerboard array of hill-and-hollow standing waves, the waves being driven by elastic chains of balls. This new phenomenon is an extension of magnetospherics.[1,2] The magnetic organization is worked out, wave phenomena are discussed, and phase relations established.

BACKGROUND

In earlier papers,[1,2] the floating organism was described. Hard cast-iron size 50 balls (about 1/50 inch) freely float in water. Magnetized, floated, and subjected to a vertical a-c magnetic field, single balls and chains of balls will orient their magnetic axes horizontally. A chain oscillates, seesawing, driven by the field. It sets up waves. Several chains and single balls may form in line on the waves, with spaces between. All this makes a backbone. Symmetric pairs and triplets may join the array along it, or at the ends, or both. Thus a linear "organism" is formed, producing standing waves which, in turn, affect and maintain the organized array. The organism may remain stationary, or it may propel itself in lifelike manner.

The units are not only spaced within the waves. There is repulsion between the balls and chains, crosswise of the vertical field. Without repulsion the balls would mass together with varied contacts. It would be active, but no organism would form.

Another phenomenon described was the sinking of a compact raft of unmagnetized balls. This is what led to the present discovery. With field off, the raft is dish-like, with the central area depressed by the weight of the raft. Now, if the field is slowly applied, repulsion tends to separate the balls; but with balls as large as size 50, stack-up dominates: the tendency to line up vertically with the field. The stronger field increases the tilting of the edges, and the central depression. The edges fold together and the raft, as a globule, sinks.

In demonstrating on July 4, 1962, it was intended to sink the raft. By chance, smaller size 80 (about 1/80 inch) balls were floated on, and they happened to be already magnetized. This raft did not sink. It was then, by accident, that the organism, theretofore one-dimensional, showed that it could be two-dimensional. Thousands of balls were poured on, with effects as seen in Figures 1 and 2.

The Free Raft

The Patterned Raft

The raft, Figure 1, is not static, as the picture might indicate. It is a shifting, changing, dynamic phenomenon. The arms are forever moving, changing in form and merging with each other. It holds the attention as few things can. A reduction of field reduces repulsion, Figure 2, and lets the arms aggregate into a more or less single-raft formation, but it too is always changing form and location.

In both, there are hills and hollows. These appear to want to form a pattern, here and there. If the field is further reduced, a compact raft forms (not shown) and at once, regularity becomes evident. There is a grid pattern, not perfect, but obvious. The raft may have several areas in which each tries to have its own grid, and these disturb each other.

Here is a remarkable organization of the ball magnets, intimately integrated with the waves they are driving. If this happens for the imperfect free raft, what might ensue if it were given a full chance to organize? The obvious step was to acknowledge the grid effect, and give the raft a square boundary.

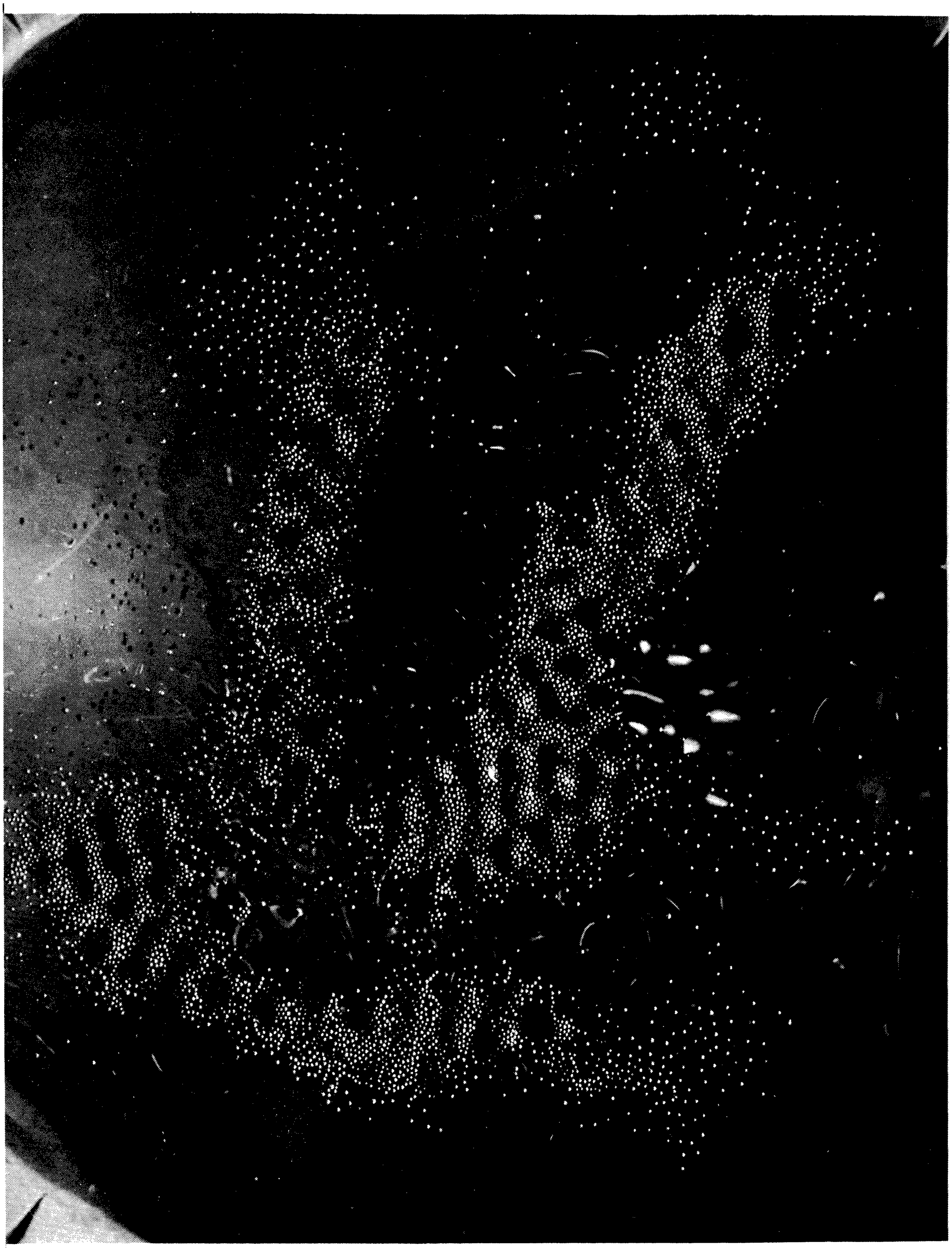

Figure 1. The magic carpet on water, in free-raft form. A dynamic carpet of magnetized balls driven by a vertical a-c magnetic field.

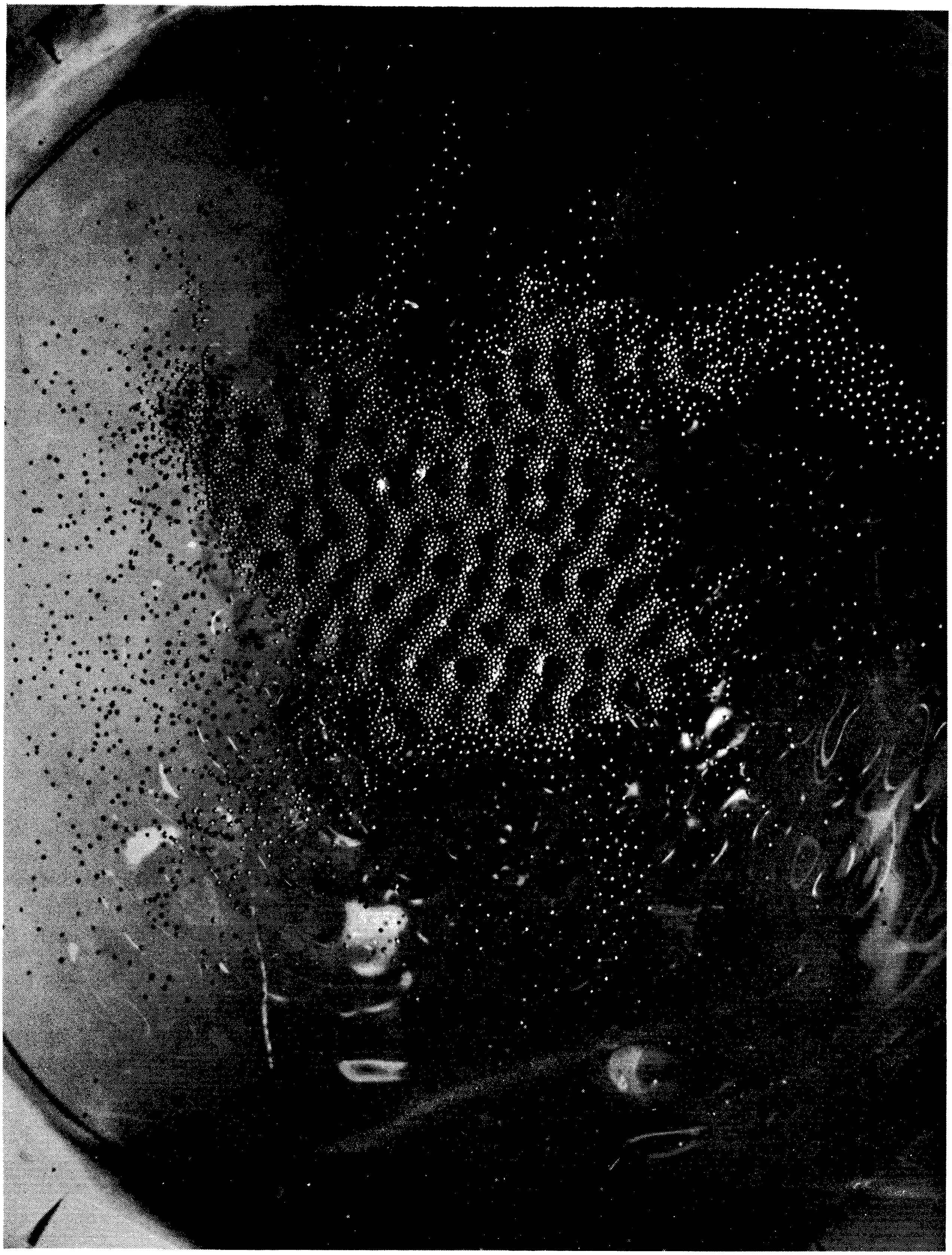

Figure 2. More compact raft, at lower field strength.

The Magic Carpet

First Results

The first frame was an aluminum strip, 1/2 inch wide, bent into a square 1-5/8 inches on a side. It was set in the water pool, with water level at the frame top, and a raft of some 15,000 size 80 balls was poured on. There was immediate success. The pattern was somewhat imperfect and changing, but was certainly trying to achieve uniformity. It promised that relative perfection might lie ahead, if conditions were improved.

A long series of experiments gradually showed that pattern perfection is sensitive to water level, levelness of frame top, number of balls for a given area, degree of ball magnetization, and strength of the magnetic field. To these five factors, add a sixth: a burnished copper plating on the balls, discussed later.

Early attempts to diagnose what was seen in ordinary light, were ridiculously far from the mark.

Stopping and Controlling the Action

By turning off the lights and using a Strobotac at line frequency, the striking beauty of the magic carpet is revealed. One sees the whole surface, Figure 3, covered with hills and hollows in checkerboard order. Using burnished copper-plated balls, the copper mounds make a dramatically lovely landscape. This stopped view of the carpet is startling; but even more striking is the effect when Strobotac frequency is changed to near 60 cycles to put the carpet

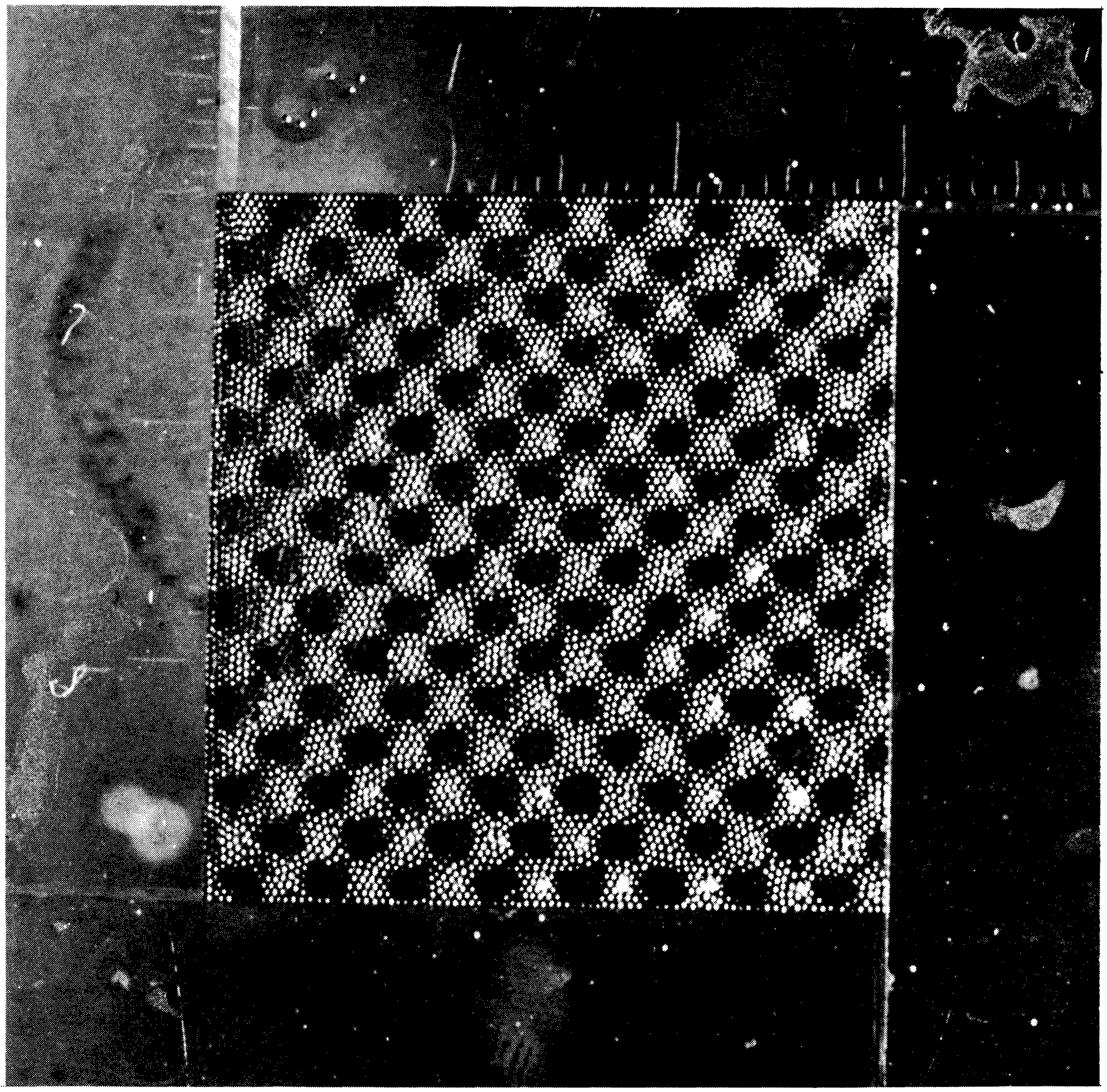

Figure 3. Checkerboard standing wave pattern of carpet in 3 cm. square. Bright areas are hills; dark areas, hollows. The array is reversed in the next half cycle.

into slow motion. The hills sink down to become hollows, and the hollows come up to become hills. Here are standing waves, with the balls riding the waves, and furnishing the driving energy.

It is now clear as to why the magic carpet is so confusing in ordinary light. The eye picks up a double pattern - one for each half cycle - the one interposed within the other. Until this is recognized, no sense can be made of what takes place. And now comes the question: how can the beautifully organized action of the carpet come about, when started from chaos?

From Chaos to Order

Let the raft be formed without the field: it is a mass of chaotically interlocking chains. Apply the field then: repulsion breaks the interlocks; the chains separate and begin to seesaw. Each would start a tiny component train of travelling waves, away from its ends in both directions. There would still be chaos, and much cancellation. But somewhere, a group of chains, magnetically oriented in parallel, would occur, making a stronger pair of wave trains.

What we will call the slope-oriented effect ensues, and it is now described. When the stronger, more dominant wave comes along, the chaotic chains it approaches may be oriented in any direction; but when they start riding the wave train, they will swing around as they oscillate, to point up and down the greatest slope of the wave - since the wave has the same frequency they have. They become slope-oriented; and in doing so, they add their driving energy and accentuate the wave train.

Thus, wave train accentuation in general, is present. But in particular, strong build-up comes from the square frame. Any travelling wave components going diagonally will strike the wall at 45 degrees, be reflected at the same angle, go to the next wall and be again reflected, and so on. These will all accentuate each other, if in phase, and furnish rapid build-up. Components in other directions tend to get lost by cancellation.

A small region of the carpet is drawn in Figure 4. The AA lines represent coincident peaks of transverse travelling waves going northeast and southwest; the BB lines, of waves going northwest and southeast. Next, an A-set of travelling waves, equal and opposite, will yield an A-set of transverse standing waves, the crests now being the AA lines, and troughs being the A'A' lines. Likewise for the B-set. Finally, the transverse A-set and B-set standing waves combine to form the observed hill-and-hollow standing waves, with peaks now at points marked P, hollows marked H, and nodes marked N.

Such a grid of hill-and-hollow standing waves has been observed in the writer's boat, in a little pool of water at the stern. Vibrated by the outboard motor, the pool usually shows ordinary wave trains; but at times, a central patch appears with trains at right angles to each other. Then the hills and hollows are identical in appearance to those of the magic carpet, and are not far from having the same size.

The magic carpet is rugged, soon re-forming after being disturbed. Stir it with a plastic rod, and it will resume regular order in a few seconds. Achievement of order is really not as fast as it seems.

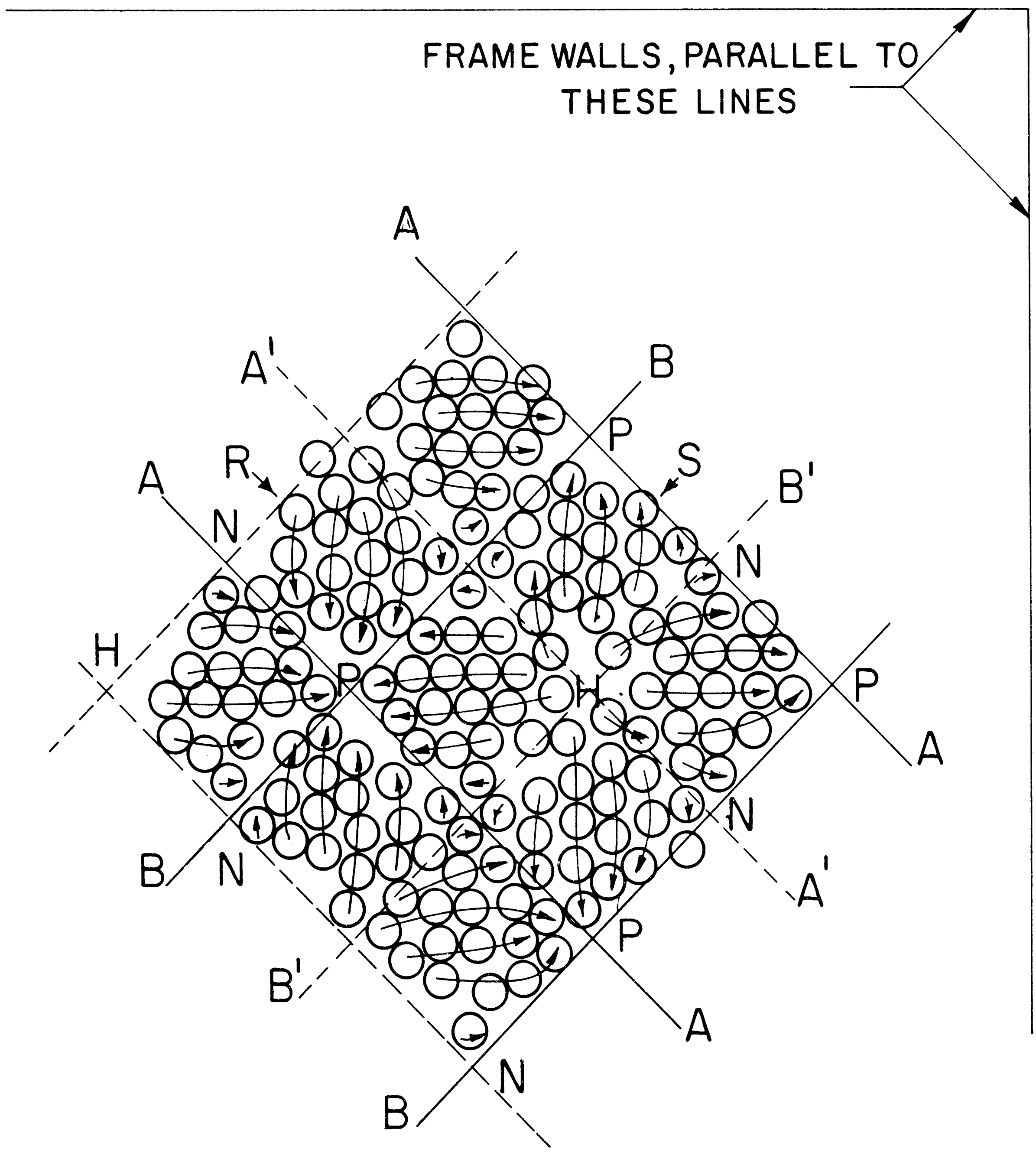

Figure 4. Magnetic organization of the carpet. (See text).

Suppose order is achieved in five seconds: at 60 cycles, the carpet has had 300 shufflings of balls, to organize them for dynamic stability.

Magnetic Organization

An approach to the problem of organization is as follows. Suppose we start with plain water, and make the hill-and-hollow waves by vibrating the frame. With a field, let the balls be poured on. Chains would form and interlock while being thrown about by the waves, with chaotic results. Next, putting the field on would break the interlocks, and the slope-oriented effect would make the chains conform to the waves as in Figure 4. Next, if the energy furnished by the electromagnetic system is sufficient, the external frame vibration could be stopped, and the balls would maintain the wave action.

It is most interesting to find that the nodes are double nodes: they are wave nodes, and also "magnetic nodes" - magnetic singularities.

The one magnetic organization that meets all requirements is that of Figure 4. At this instant, an upward field has tilted the North ends of chains up toward the peaks, and the South ends into the hollows.

Parallel Waves

The dominant pattern so far discussed is due to diagonal waves, reinforced by succeeding 45 degrees reflections, and having the checkerboard pattern. There is another possibility. What if, somehow, parallel waves initially happened to dominate? Such waves, parallel to two frame sides, would build up by back-and-forth reflection between those sides.

And, if the other set of parallel waves also took place, the complete magnetic organization might occur, and such a pattern - a square pattern rather than checkerboard - might ensue. In all of the very numerous trials, this happened only twice. The first time, the pattern was crude, and soon broke up to re-form in the diagonal mode. Some weeks later, the second instance came. It was much more regular, and persistent, but it never achieved anything like the relative perfection of the diagonal mode pattern. Perfection cannot be expected, since the two sets of back-and-forth waves cannot very well correct each other's deficiencies; whereas, in the usual diagonal mode, the continuous 45 degree reflections of waves, once started, should serve to iron out imperfections and tend to shuffle the balls into a "perfect" magnetic organization.

There is purpose in mentioning this rarity. Sometimes the usual pattern shivers. Irregular shivers may indicate ball insufficiency, or other trouble; but periodic shivering, difficult to describe, can occur. With the Strobotac at near line frequency, alternate bands of stripe, or even alternate stripes, are sometimes seen to shift lengthwise a little, abruptly. This is not understood. Perhaps it is due to a small parallel wave component. But if so, how could the regular magic carpet organization make such a component? We cannot find such a driving source in Figure 4, if equal numbers of balls are assumed to be in each of the smallest squares. A gang of balls in the R-square, trying, with like gangs, to generate parallel waves, would be nullified by the S-square and its mates. However, while the regular pattern is still forming, a parallel wave component could use the slope-oriented effect to put fewer chains in, say, the R-gangs, and more in the S-gangs. This would maintain a parallel wave component.

This may happen, for something is needed to explain why the regular pattern sometimes prefers to have unequal numbers of hills, counted each way. It might account for another imperfection: a diagonal row starting in one corner of the square may miss the other corner by a notch or two. Of course, the anomalies may also be saying that conditions are not ideal: that the balls, for example, are notably imperfect.

Pattern of Unframed Raft

The build-up for diagonal waves accounts for the carpet pattern in its frame. But, with a compact, free raft floating in a large round pool, reflected waves would be weak, and more or less of random effect. Why then does the free raft do its best to display the carpet pattern? Presumably, in an infinitely large set-up, great patches would occur, with the magic carpet geometry. They would not need reflection, being self-sufficient; but, why take this form? Why not a triangular, or hexagonal arrangement? Now, to achieve dynamic stability, there must not only be a stable wave form; there must also be a stable magnetic organization to fit that form and also serve to shape and drive it. This double restriction seems to limit possibilities to the single one portrayed. No others have been found that satisfy all conditions.

Frames Other Than Square

These analyses seem to be borne out by tests run with various frames. Rectangular frames work as well as square frames, even when re-entrant corners are added. But the carpet refuses to have a new pattern imposed on it by round or hexagon frames. The regular pattern forms as best it can, over much of the area, and with outer regions confused and irregular.

Tight and Elastic Chains; Ball Movement

Some tight magnetic chains are seen in arm margins, Figure 1, where wave action is subdued. A tight chain is one with the balls stuck together. More appear in Figure 2, with weaker field and less repulsion. Now, with balls properly magnetized, repulsion by the field can separate the balls, and yet let them retain chain identity. This makes an elastic chain. Elastic chains are of paramount importance to the magic carpet.

Proof comes in motion pictures taken at 3200 frames per second, and shown at normal speed. A few balls move slightly sidewise, but nearly all of the balls have virtually no horizontal motion. Their paths are vertical. If the chains are tight in the flat period when hills and hollows are smoothed out, then, at maximum wave amplitude, a chain is stretched in fitting to the profile of the wave. The stretch is considerable: by visual inspection, the difference in level from peak to hollow is about equal to the wave length.

There is more evidence. These balls had been copper-plated and burnished,[2] for magnetospherics. After much use, the plating may have worn: it became difficult to get a good carpet. After replating and reburnishing, performance was much improved. Plating prevents iron-to-iron contact, making it easier for the field to turn tight chains into elastic chains.

In Figure 3, the 3 cm. square has about 6,800 balls. They have ample room to maneuver, for they cover only 0.6 of the flat-water area. They are divided among some 125 units, a unit being a square, Figure 4, having four adjacent peaks for corners. This gives about 54 balls per unit, which is roughly the number drawn in the figure.

The Magic Carpet, and Implications

First and foremost, the magic carpet is a fantastically beautiful demonstration of how a complex interweaving of the laws of physics can start with chaos, and bring it into complete dynamic order. In watching the cycles of movement (Strobotac or motion pictures) and realizing that these iron balls are perfectly adapting themselves at 60 times per second, a better appreciation comes of how molecules, atoms and electrons, on their incomparably smaller scale, not only can achieve order, but can make their movements at an incomparably higher frequency.

Colleagues viewing the carpet have repeatedly mentioned similarities to phenomena in wave guides, and to plasma frequency. These ideas are passed on. In the gyrations of the free raft with its changing arms and striations, the writer has often seen formations reminiscent of galactic formations. Astrophysicists may wish to make their own observations. Just possibly, a helpful analogy for some galactic behavior might be present.

The magic carpet also may be our only example of self-energized standing waves, in which the driving forces come from an intimate part of the wave itself.

Wave Length

In Figure 3 the wave length (diagonally) is about 2.8 mm. Approximately, the wave length remains constant, for frame dimensions from 1 to 4 cm., and water depths from 1/8 to 1/2 inches. Since water waves alone would have the wave length depend on both frame size and water depth, it is clear that water wave theory does not explain this phenomenon. What then does fix the wave length? The clue comes from watching smaller formations, as in the linear organism. The backbone will be made of chains of from one to six balls, separated by short gaps. Or again, strictly isolated chains will have two or four balls, sometimes five, occasionally six. Obviously, when a chain is too long, it is too weak to maintain integrity when acted upon by the water movement it sets up, and will break. Now note that in Figure 4, chains have up to five balls, and six might at times occur. Thus, it appears that the magnetic organization can have, and does have, about a five-ball chain limit, and that this is the factor that determines wave length. As far as the water is concerned, it is in forced vibration.

The simple guess would be that with balls of half the diameter, wave length would be halved. However, ball mass, attraction between balls in a chain, repulsive forces, and field action on a chain, would not all necessarily change proportionately with change in diameter. The actual result will have to await trial.

One test was run at 180 cycles, and no pattern was observed. It is presumed that chain length was reduced to about one ball, and that the required magnetic organization could not take place.

The Field, and Ball Magnetization

The balls are hard-cast iron shot, meant for shot-peening, air-blast cleaning of castings, and so on. The raw shot is heavily loaded with imperfect shapes. Selected balls were winnowed out,[1,2] and further selected by slow visual inspection. There are no true spheres - merely a majority of pretty good spheres. The diameter is close to 1/80 inch, but varies each way by perhaps 10%. The balls, in a plastic bowl, are magnetized by moving an Alnico U magnet underneath several times, with a spacer between bowl and magnet. Spacer thickness is critical, to be found for any one magnet only by trial. Balls weakly magnetized will separate by repulsion and be too inactive. If over-magnetized, it takes too strong a field to break interlocks and have elastic chains: the carpet goes wild. Note this: good performance of the free raft requires balls more strongly magnetized, than for the framed carpet.

It is interesting that very good carpet performance occurs with "diluted" balls (suggested by Professor Richard E. Balzhiser) - which is done by magnetizing, say, only half of the balls.

True spheres such as ball bearing balls might give better and more consistent performance; but this must await trail.

A pair of Helmholtz coils could furnish the vertical field. The writer uses the two coils already available for 'spherics.'[1,2] The r.m.s. field density for best results is about 350 maxwells per sq. in. (54.5 gauss); but it must be remembered that field strength depends on degree of ball magnetization.

Phase Relations; Power Input

Phase relations would be as in Figure 5a, if the carpet had no losses. The upward field in the first half cycle is matched by all peaks being North, maximum wave and field amplitudes occurring together. Likewise, but in reverse, in the next half cycle.

The power input curve (dash line) can qualitatively be drawn. Considering a magnetic chain as a dipole, instantaneous power is force times vertical velocity of poles of the dipole; force being proportional to field B. Power is zero at zero B; also when pole velocity is zero, at maximum wave amplitude. From 0 to 90 degrees, the poles are going with the forces on them, and energy is put into the waves. Input energy is taken positive. From 90 to 180 degrees, the wave carries the poles against the forces on them, and puts an equal amount of energy back into the power supply. Net energy transfer is zero. If vertical movement is taken as sinusoidal (and it looks very much like this, in slow motion) then the power wave is a double frequency sine wave.

Now suppose that the above lossless system prevails up to the start of the cycle, and that then, loss is introduced. The standing wave would not rise as much, its peak amplitude would lag; and when the transient thus started ends in a steady state, the conditions of Figure 5b would prevail. Positive power exceeds negative power, and there is a net energy input.

The drawing shows maximum wave amplitude lagging 45 degrees. This is approximately what was found, by use of a synchronous contactor adjustable as to angle and set to zero by oscilloscope, devised for firing Ne 2 (neon) bulbs to illuminate the carpet. A 45 degree lag was used for the Figure 3 picture, showing the carpet about at maximum amplitude.

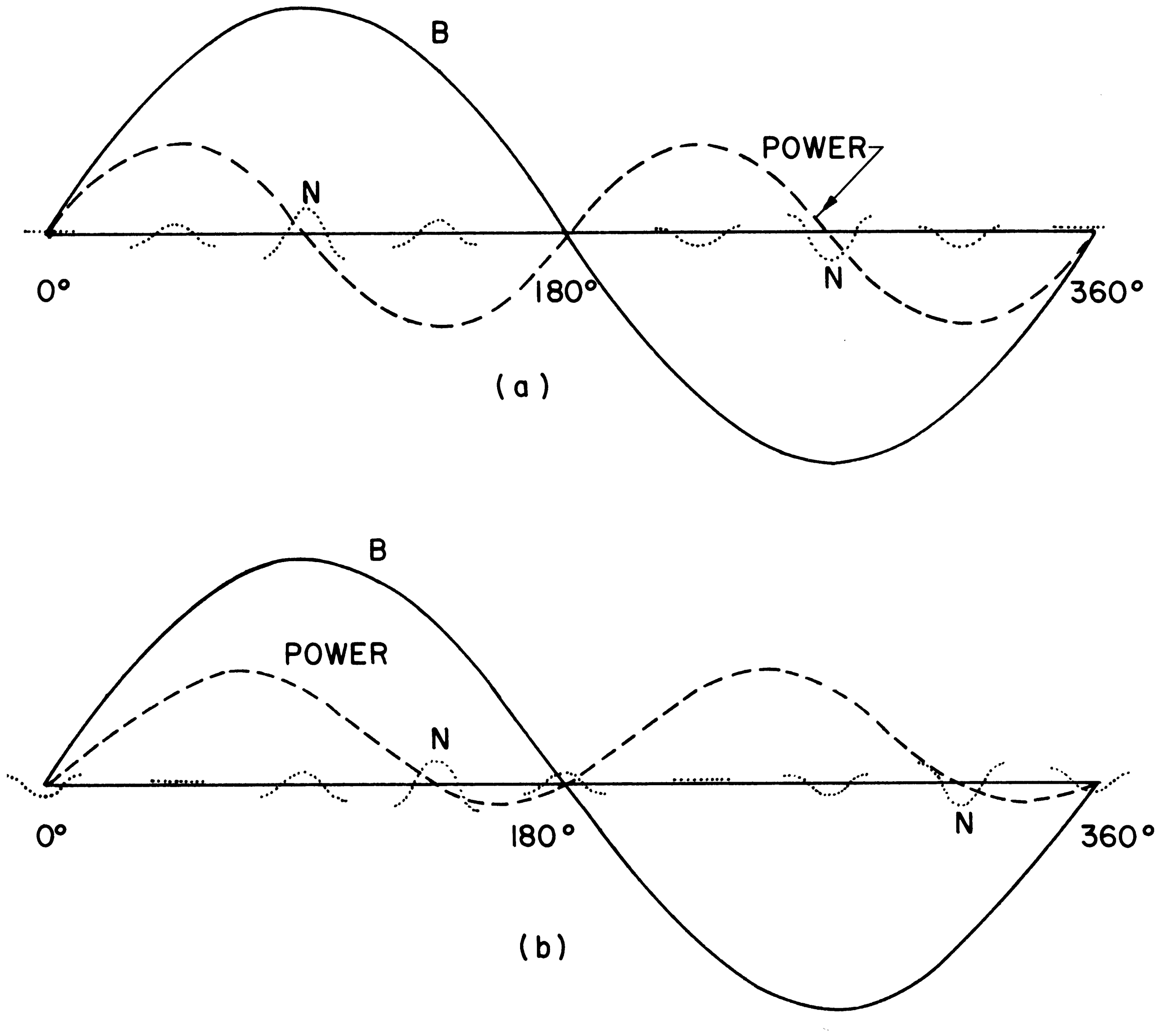

Figure 5. Phase relationships. The carpet lags about 45 degrees behind the alternating field.

Operating Techniques

Balls dropped too far will pierce the water film and sink. To pour the balls close to the surface, and direct them to remaining bare spots, a feeder is needed. This is a waxed paper soda straw bent at right angles in inch from one end, with the top of the boot slit open. The balls will cling together in the boot, until some field is turned on to induce activity; they then stream out. A medicine dropper can be inserted through the carpet for accurate adjustment of water surface to frame top level. The frame, Figure 3, is made of four pieces of Plexiglas, held to plate glass by modeling clay.

If the carpet shivers considerably with full field, it needs more balls. Fed onto the carpet in limited numbers, most of them promptly fit in. Those who work with monolayers should certainly observe the others, busily skipping around on the monolayer, until they find a home in it.

After operation, balls are collected on the end of a smooth Alnico rod magnet and dried on a paper towel. The retriever magnet overmagnetizes them. To demagnetize, the balls are put in the bowl, and the bowl bottom is moved in contact with the upper coil in which high momentary current is used.

CONCLUSIONS

A raft of thousands of tiny magnetized balls, floating on water in a square or rectangular frame, is turned into a dynamic magic carpet of ball-coated hill-and-hollow standing waves organized in checkerboard fashion, by applying a vertical a-c magnetic field.

An extension of magnetospherics, this new phenomenon is sensitive to a number of physical factors. These have been worked out experimentally and described, so that others may duplicate the performance.

Why the physical laws involved should bring order out of chaos and then sustain that dynamic order, requires analysis of the magnetic organization of the carpet, discussion of wave action, and phase relationships. These have been worked out and discussed. The wave length is not dependent on frame size or water depth, and thus is not to be predicted from water wave theory; instead, it is determined by the chain-length limit set by the organization itself.

This may be our first example of self-energized standing waves. The magic carpet is a thing of beauty; and as a visual demonstration of how the complicated interplay of natural forces can quickly establish order out of disorder, it may have few competitors.

Various observers have remarked on similarities to wave guide and plasma frequency phenomena.

When the carpet is allowed to roam at will in a large pool, forming arms and striations, effects are seen reminiscent of galactic formations. It is suggested that astrophysicists observe these effects for themselves: the interest aroused might possibly lead to the discovery of a useful analogy.

Every aspect of the phenomenon is open to improvement, and to further research: experimental research into the effect of ball size, surface tension, specific gravity of fluid, frequency, and so on; and theoretical analysis to round out the picture, and perhaps to find analogs for other phenomena.

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2. Electrospheric and Magnetospheric Phenomena, A. D. Moore. AIEE Transactions, Communications and Electronics, Vol. 81, 1962. (Much the same as 1, but brought up to date in some respects).