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Electrodynamic Activities and Their Role in the Organization of Body Pattern*

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Abstract—This paper reports some of the highlights of our investigations (both published and in progress) into the role of electrodynamical activities in the organization of body pattern in ***Drosophila.*** 1. Exposure of populations of synchronously developing embryos for 30 minutes to weak static magnetic fields (0.5 to 9 mT) during the first three hours of development results in a high proportion of characteristic body pattern abnormalities in larvae which hatch 24 hours later. As the energies involved are below thermal threshold, there can be no significant effect unless there is a high degree of cooperativity or coherence in the pattern determination processes reacting to the external field (Ho et al., 1991a). 2. Developing embryos show profuse electrical activities (recorded with microelectrodesplaced within the polar pockets) starting at least as early as 40 m after fertilization and continuing well into cellularization. The activities are highly patterned, and evolve in the course of development. They may reflect changes in polarization of the embryonic field associated with the coherent excitations predicted by Frohlich (1968;1980). 3. Populations of synchronously developing embryos show self-emission and light rescattering characteristics that also change with developmental time. In addition, embryos less than 40 m old exhibit an entirely new phenomenon in the form of intense luminescent flashes which can appear any time from one to 20 minutes, and up to 8 hours after light stimulation. These super-delayed luminescent flashes may result from cooperative interactions among embryos within the entire population, which serve to synchronize development to external light as Zeitgeber (Ho et al., 1991b).

Introduction—Biological Organization and the Embryonic Field

By far the most ubiquitous biological phenomenon that has as yet no satisfactory explanation within science is the organism itself in particular, how a relatively featureless fertilized egg can turn into a shapely, highly differentiated organism in the process of development. Most biologists believe in what

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amounts to the occult when it comes to development, they invoke the action of genes which turn on other genes which turn on other genes that somehow make the conglomerate of characters in the organism. Some, like ourselves, are impressed with the fact that organisms are not constructed piece-meal, but are organized wholes beginning with the egg. The problem of development is how the global embryonic field generates pattern at the outset (see Ho et al., 1991b for a detailed discussion).

But what is this embryonic field? The idea that the embryonic field is electrodynamic goes back at least to Burr and Northrup (1935), who detected electric fields around both developing and adult organisms. Becker (1962) confirmed those findings, demonstrating the existence of DC fields on the surface of intact organisms which change dramatically as the result of both anaesthesia and injury. He also identified DC currents that are specifically associated with limb regeneration in salamander (reviewed in Becker, 1990). Using the more sophisticated vibrating probe technique, Jaffe (1982) was able to detect transembryonic ionic currents in all developing systems examined. These currents typically appear before any overt sign of development, suggesting that they may play a role in setting up major body axes and pattern in the embryo, which somehow mirror the electrical field gradients and polarities. However, no direct causal connection has yet been established (see Nucitelli, 1988). The possibility remains that the currents are themselves manifestations of a more fundamental process.

A further clue to biological organization comes from a series of reports suggesting that organisms including humans are sensitive to very weak electromagnetic fields—both natural and artificial in origin—within the entire frequency spectrum from the extra low to the microwave range (reviewed in Presman, 1970; Frohlich, 1980; Becker, 1990). As the energies involved are often below thermal background, the reports are regarded with a great deal of skepticism by the orthodox scientific community. They conclude that no known mechanism could account for the effects, even though there is now indisputable evidence that chronic exposure to weak electromagnetic fields are associated with increased incidence of cancer and other illnesses (Schulman, 1990). In this connection, Frohlich (1968;1980) has earlier suggested that, given the dielectric nature of all biological molecules—especially those constituting biological membranes—metabolic energy could well be stored in the form of electromechanical vibrations. Under certain conditions, those vibrations will condense into a coherent or collective mode—which may be a stable or metastable strongly polarized state (perhaps not unlike the DC fields observed by Becker, 1962, and others) or an oscillating one—when organisms will exhibit extreme sensitivity to external electromagnetic fields. If these 'coherent excitations' are involved in biological functioning, that would explain the biological effects of weak electromagnetic fields.

The idea of coherence appears to be the key to explaining many of the most characteristic properties of the living state. These include extreme sensitivity to external cues, amplification of incoming signal, rapid and efficient transfer

and transformation of energy, and long-range dynamic order (see Ho, 1989). Independent evidence for the existence of coherence comes from biophotons research carried out by Popp and his coworkers (see Popp et al., 1981), who conclude that the living systems may indeed be coherent in a broad range of frequencies which are coupled together effectively to give a single degree of freedom. This coupling of a band of modes was also predicted by Frohlich (1980) from theoretical considerations, and in his model, accomplished via a 'heat bath' at a specified temperature, enabling instantaneous energy exchange between modes. This has prompted us to consider the possibility that global dynamic coherence may be particularly instrumental in generating the first patterning during development, and that the organizing properties of the embryonic field may be due to an underlying coherent electrodynamical field (Ho, 1989).

A number of observations offer circumstantial evidence for the involvement of global coherence in pattern formation. First, all embryos begin development with a series of cell or nuclear divisions that occur simultaneously and synchronously over the entire embryo. Second, the size of the embryo at which pattern is determined is of the order of 1 mm in all organisms regardless of the size of the adult or its rate of development. This suggests a limit imposed perhaps, by the requirement for global coherence. Significantly, growth occurs only *after* body pattern is determined and registered by the expression of specific genes, best-documented in the case of *Drosophila.* This also coincides with the decay of global synchrony in the embryo. As growth and differentiation proceed, organized structures are laid down sequentially which facilitate both the maintenance of coherence on a'larger and larger scale, as well as the evolution of domains of local dynamic autonomy, which could either be effectively decoupled from the whole or coherently vibrating with it, albeit with different local frequencies (see Frohlich, 1980). The living system may owe its dynamic flexibility and stability to an alteration of its effective number of degrees of freedom according to functional state.

In this paper, we report a number of related observations on the early embryo: the effect of weak static magnetic fields on pattern formation, the electrical activities, and biophoton emission characteristics all of which point to coherence and cooperativity in the processes determining body pattern. Furthermore, under certain conditions, long-range cooperative interactions may extend over the entire population.

Methods

Drosophila melanogaster was maintained at 25°C in a 12 h light/dark regime as described by Ho et al. (1987). The Oregon strain was used for all of the studies except for some measurements of electrical activities where the Canton strain was used instead. *Drosophila* eggs are fertilized at oviposition, when development begins. It is therefore possible to collect large numbers of embryos that are synchronous to within one minute of development.

Exposure of embryos to weak static magnetic fields was performed as described elsewhere (Ho et al., 1991a) using a Helmholz coil fitted with an adjustable teflon holder in the centre which could be turned through 90°, enabling us to expose the embryos in two perpendicular orientations of the field.

The electrophysiological methods are as described in Nicholson and Rice (1988). The electrical activities of the developing embryo were first discovered while measuring changes in specific ion concentration with ion-selective microelectrodes (Ho and Nicholson, unpublished), and were confirmed in subsequent measurements using ordinary microelectrodes. The embryo, with its chorion removed, was attached by hydrophobic interactions between the vitelline membrane and the plastic surface of the petri dish. It was immersed in insect Ringer with 4 mM k^+ (instead of the 70mM that is recommended, as our ion-selective microelectrode measurements consistently gave concentrations near the low end) and 8.33% Dextran (mol. wt. 77800, Sigma, St. Louis Montana). In experiments involving ion-selective measurements, a double-barelled glass microelectrode (Ag/AgCl leads) with tip diameter of about 2 μm was filled with 0.2 M NaCl in the reference barrell and with 0.2 M solution of the ion of interest in the ion-selective barrell closed at its tip with a hydrophobic membrane containing a specific carrier for the ion. The microelectrode was inserted into the posterior or anterior polar pocket inside the vitelline membrane but external to the embryo. Potentials were measured against a low resistance silver/silver chloride 0.3 M KCl/Agar indifferent electrode, and the signals amplified by a D.C.-coupled amplifer. The ion-specific potential was obtained by subtracting out the reference potential. In this paper, we shall be concentrating only on the potentials directly recorded by the reference electrode. In measurements of electrical potentials only, single barrelled micropipettes with tip diameter of about 0.5 to 1 μm were used, and the indifferent electrode was filled with insect Ringer in agar, in order to avoid leakage of potassium into the bathing solution. The embryos were stuck down in a shallow petri dish with non-toxic surgical glue.

For photon-emission and rescattering measurements, three to seven-day old flies, cleared of retained eggs, were anaesthesized with carbon dioxide and transferred directly into a quartz cuvette (2 × 2 × 6 cm) where they were confined and encouraged to lay eggs over all the available surface for 3 to 5 min (depending on how long they take to recover from anaesthesia), after which, the flies were removed. The cuvette containing the freshly laid eggs—which remained in situ where they were deposited by the females—was transferred to the photon-detecting apparatus and maintained in a humid atmosphere for the duration of the measurements. All measurements were performed at 25°C as previously described (Popp et al., 1981).

Figure 1 is a diagrammatic representation of the developmental events and approximate time-table in Drosophila embryogenesis, based on Foe and Alberts (1983), Foe (1989), and our own observations. The nucleus of the fertilized egg undergoes a series of synchronous divisions without cell divisions.

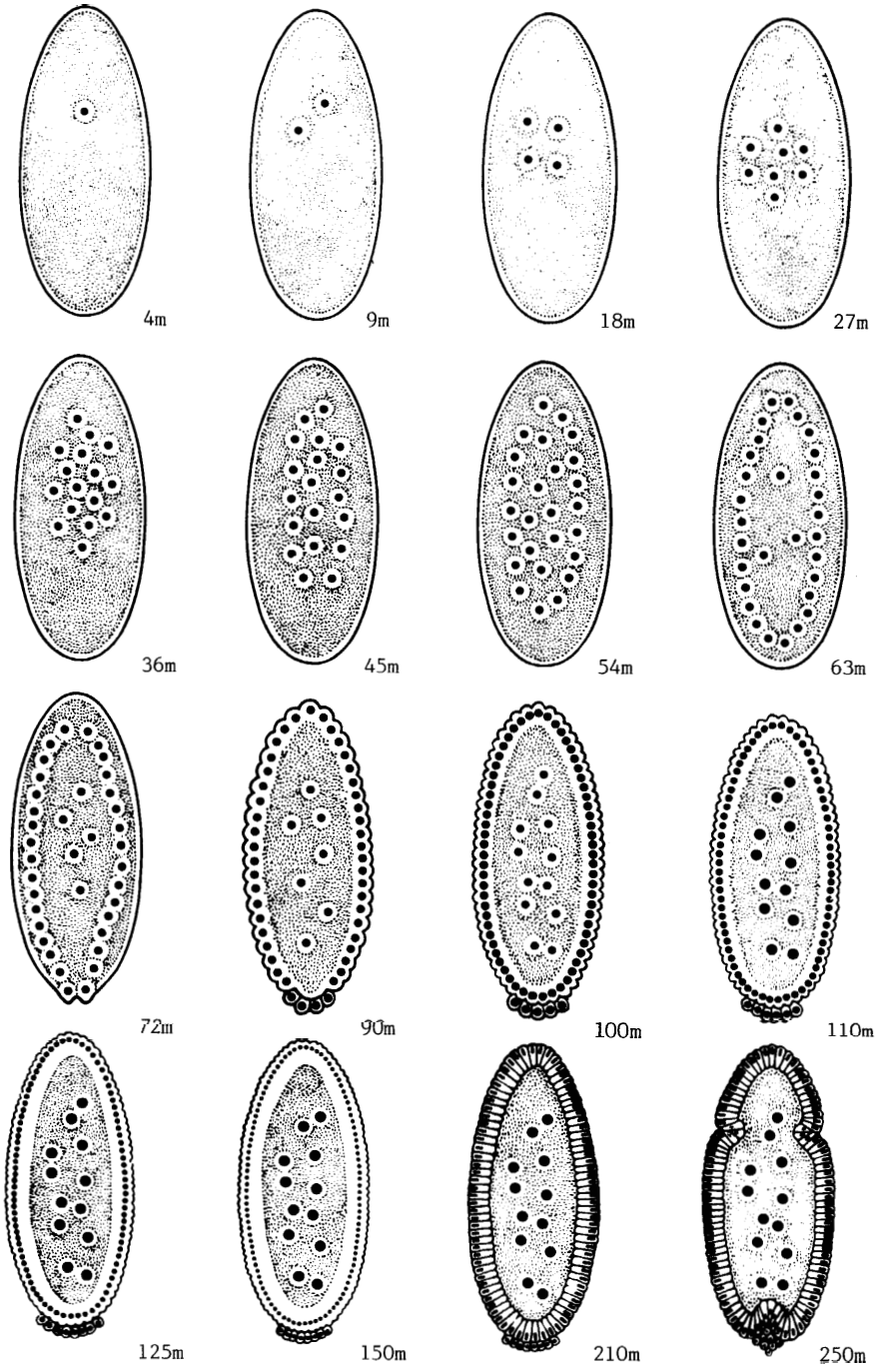

Fig. 1. Diagram of developmental sequence of early Drosophila embryos with approximate time-table at 20°C (see text for details).

After six to eight cycles, most of the nuclei migrate to the layer of cytoplasm (the periplasm) just beneath the plasma membrane to form a syncytial blastoderm where two more nuclear division cycles take place. At the posterior pole, a number of the nuclei become pinched off to form pole cells, which are the future germ cells. The rest of the nuclei undergo 4 more divisions before cellularization takes place over the entire blastoderm. The resultant cellular blastoderm gastrulates almost immediately. All the major pattern determination events have occurred by cellularization (see Ho et al., 1987, and refs. therein).

Results and Discussions

1. Effects of Weak Static Magnetic Fields

a. Abnormalities Induced

The major abnormalities are shown in Figures 2 and 3. Typically, the effects include the following. (a) Inhibition of the *initiation* of patterning processes resulting in a total absence of structure (Fig. 2a). (b) Disturbance to either or both anterior and posterior extremities, resulting in the absence of head or tail of both (Fig. 2b-e). The reduction, and especially the absence of the posterior end (Fig. 2d, e) is significant, as this end is very resistant to perturbation by other agents (Ho et al., 1987). (c) Twisting and/or rotation of the segmental pattern (Fig. 2f and Fig. 3b–h), which in the extreme case, converts the entire stack of consecutive segments into a continuous helix (Fig. 3h).

All the defects, in particular, the variously twisted and rotated patterns are specific to magnetic field exposure, and are seldom, if ever, found in perturbations with other physical or chemical agents such as temperature shocks, exposure to ether vapour, etc. (Ho et al., 1987).

b. Effect of Field Strength, Time, and Direction of Exposure

The results of exposure to magnetic fields oriented along the dorsal/ventral axis are summarized in Fig. 4. As can be seen, there is a flux-density related increase in abnormalities from 0 to about 3 mT. Thereafter, the percentage abnormalities remains level at about 17%. Moreover, it does not appear to increase appreciably with increase in exposure time: The exposure to 9 mT was continuous for 24 h under a small bar magnet and it gave very similar results to lower field strengths applied to 30 minutes typically between 60–90 minutes after oviposition. This suggests that the embryos are sensitive to the effects of the magnetic field within a *restricted time window.* Indeed, embryos exposed at 3–4 h after oviposition did not develop abnormalities above the level of the controls. At 3.5 mT perpendicular to the dorsal/ventral axis the hatching rate, nea, and abnormalities with respective standard deviations, were: (78.10 ± 2.12)%, (18.73 ± 2.00)% and 3.96 ± 1.00)% (n =

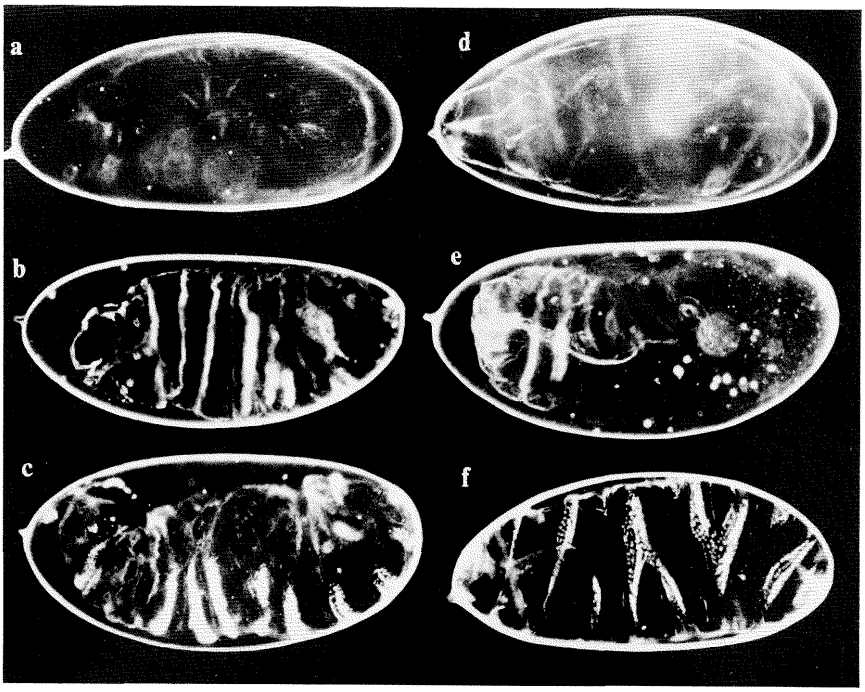

Fig. 2. Abnormalities among unhatched larvae exposed to static magnetic fields. (See text for details.)

379), compared to the matched control values of (74.05 + 2.28)%, (24.05 + 2.22)% and 2.16 + 0.76)% (n = 370). This is consistent with previous findings indicating that pattern disturbance by environmental agents is minimal after the first three hours of development (see Ho et al., 1987 and references therein).

A less extensive series of experiments were performed with the magnetic field oriented perpendicularly to the dorsal/ventral axis, albeit randomly with respect to the anteroposterior axis. (The randomness arose because the embryos were allowed to remain *in situ* after they were deposited by the female flies in order to minimize nonspecific mortality.) The percentage of total abnormalities was increased compared with the previous orientation, although there were no new categories of defects. Again the category 'twisted' appeared at the highest frequencies (see Ho et al., 1991a).

c. Discussion

Our results confirm the findings of Ramirez et al. (1983), demonstrating in *Drosophila* a decrease in hatching rate (and hence viability) as the result of exposure to weak static magnetic fields. The identification of specific morphological abnormalities, however, is new.

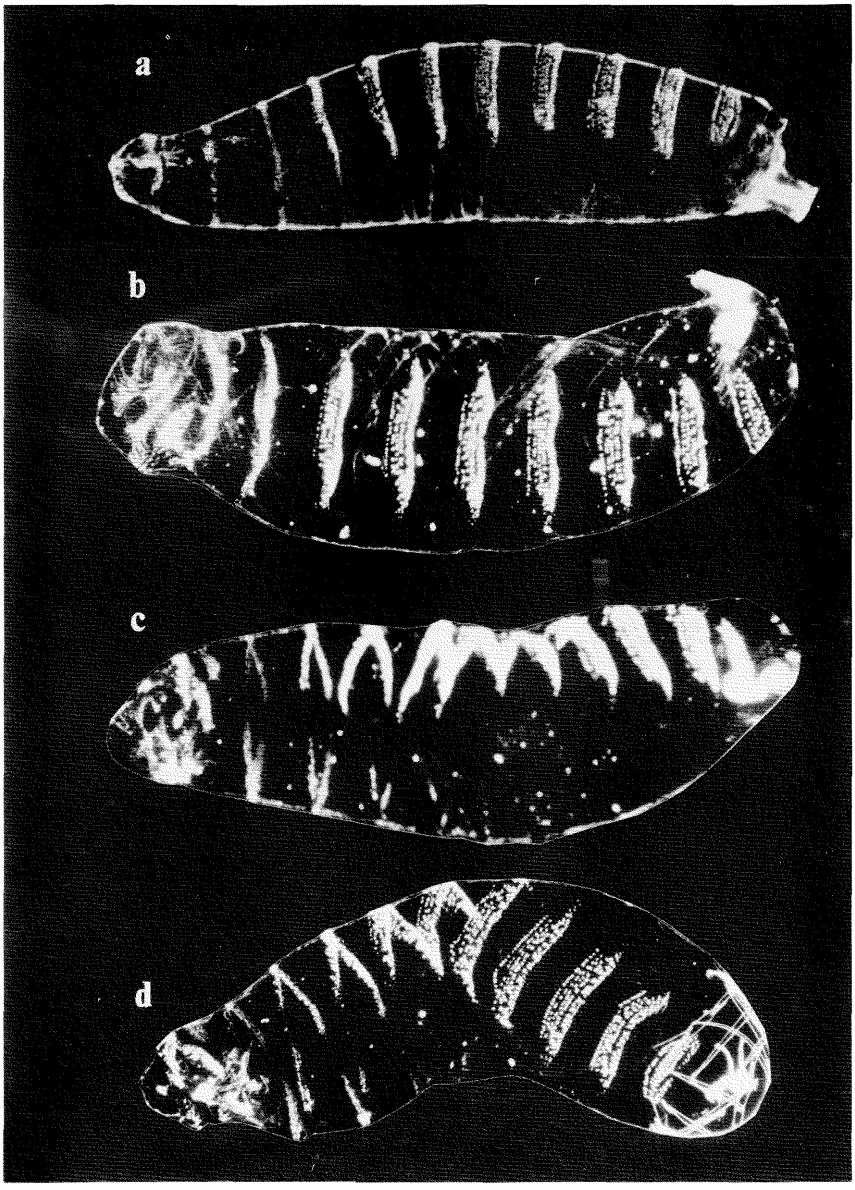

Fig. 3. Abnormalities among hatched larvae exposed to static magnetic fields. a. Normal first instar larva; b–h, abnormal larvae with various twisted and rotated patterns. (See text.)

All in all, the magnetic field appears to cause specific global and local disturbances to the developmental field *distinct from those resulting from other environmental agents*, suggesting that the developmental field includes dielectric, ionic, magnetic or electromagnetic components.

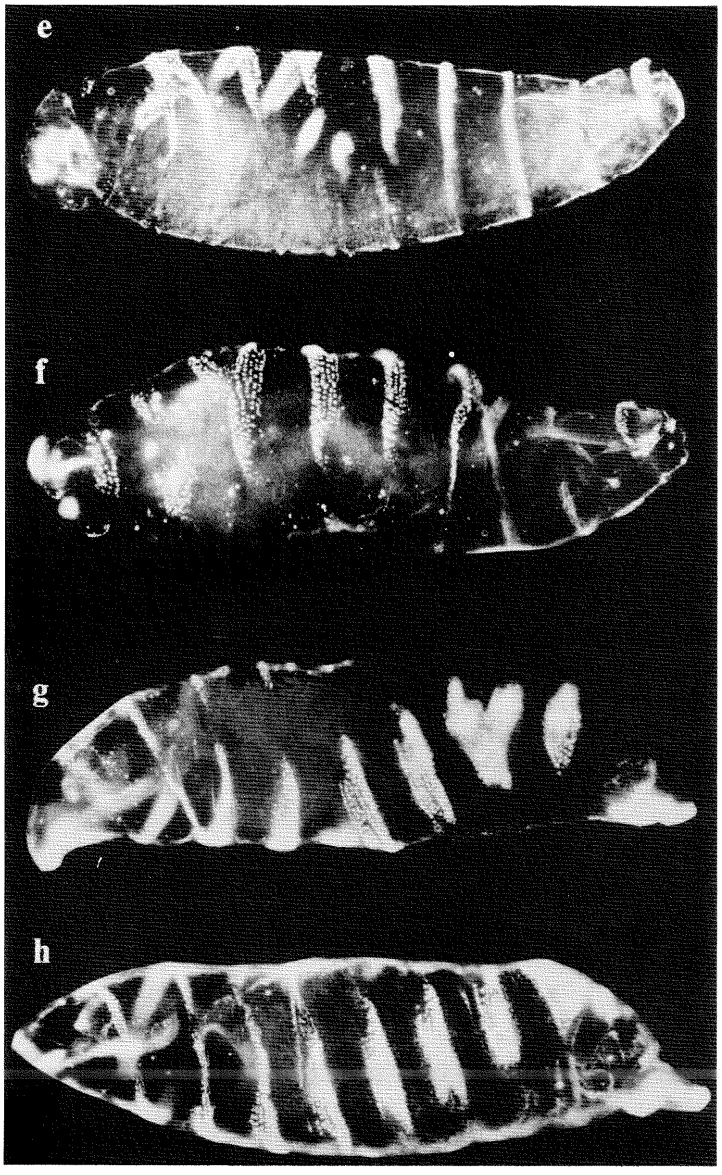

Fig. **3.** (Continued)

Let us consider the transembryonic ionic current in early *Drosophila* embryos (Overall and Jaffe, 1985), which typically flows into the anterior pole and out around the posterior pole, and is believed to be carried mainly by Na^+. The Hall effect field generated by the external magnetic field on the moving ions is estimated to be a maximum of 10^{-11} Vm^{-1}, compared to the

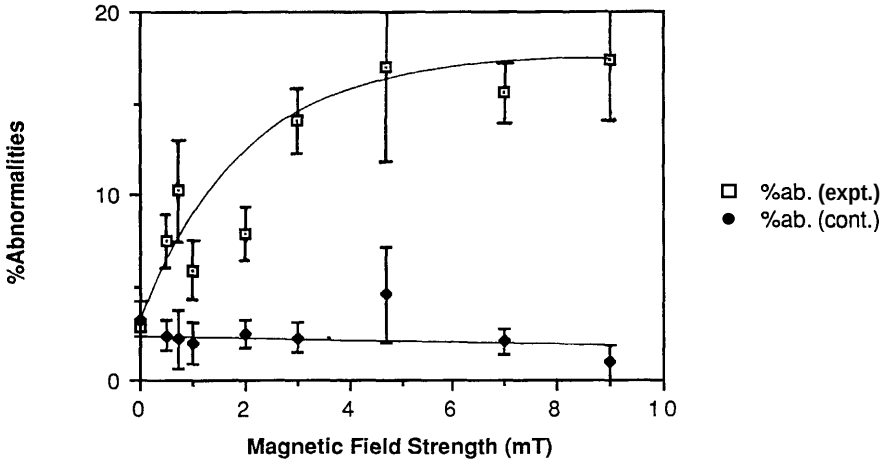

Fig. 4. Percent abnormalities as a function of magnetic flux density. Exposures were along dorsal/ventral axis. Vertical bars represent standard deviations; upper curve, exposed to magnetic fields, lower curve, matched controls.

electric field across the embryonic membrane, which is of the order of $10^{7}\mathrm{Vm}^{-1}$. This indicates that ionic currents *per se* are not the fundamental process in pattern determination. Similarly, the direct influence of the external magnetic field on individual magnetic dipoles in the cell membrane is estimated to be at most $\sim 10^{-25}$J, which is several orders of magnitude below the thermal background at room temperature, $kT \sim 4 \times 10^{-21}$J. It therefore seems that there can be no significant effect unless the magnetic field is acting via a high degree of cooperativity among the molecules involved in the processes of pattern determination. One form of such cooperativity, mentioned in the introduction, is Frohlich's (1980) coherent excitation. We shall see how the electrical activities fit into such an interpretation.

2. *Electrical Activities in the Early Embryo*

a. *Pattern of Activities*

From the results we have obtained so far, it is evident that the pattern of the changes in extracellular electrical potential recorded at the polar pockets is extremely rich and dynamic, spanning timescales, ranging from hours to minutes for abrupt oscillatory changes in field potential to spiking action potentials between 1 to 30 hz. The activities are strongly reminiscent of those from nerve cells, yet they appear at least as early as 40 minutes from the start of development, at around nuclear migration stage, and persisting through to cellular blastoderm. During most of this period, there is little or no cellular organization. The changes in discharge pattern are correlated with developmental stage, but it would take many more experiments to define them properly. The ionic potential for $K+$ also undergoes slow changes within the same

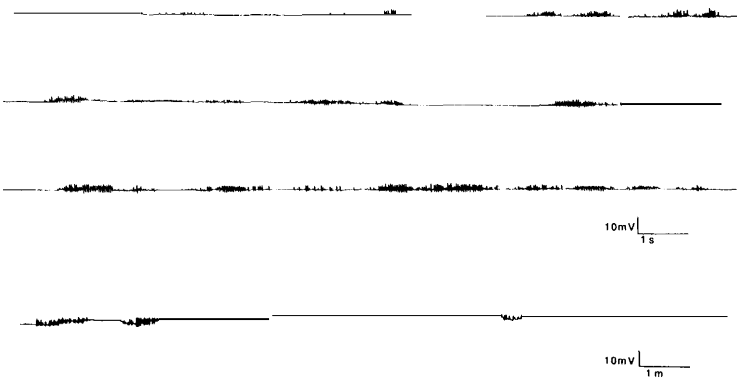

Fig. 5. Successive frames from a continuous recording at the posterior polar pocket during early syncytial blastoderm stage. (See text for details.)

period (Ho and Nicholson, unpublished), although its relationship to the field potential is not direct, indicating once again, that ionic currents are probably not central to the pattern determining events of the embryonic field. We are now concentrating on measurements of electrical potentials only. (Progress is slow due to a total lack of success in obtaining grant support, despite much effort on our part.)

Figures 5 and 6 give examples of our recordings. As can be seen, the electrical activities are richly patterned with motifs and phrasings—rather like a musical composition—evolving in the course of development with both frequency and amplitude modulations. The motifs contain submotifs within, and are at the same time part of a larger pattern.

Figure 5 contains successively later frames (top to bottom) of a continuous recording from the posterior polar pocket between 61 to 80 minutes of development (early syncytial blastoderm). The activity pattern consists initially of successive volleys of mainly upward spikes (about 30 hz), each volley of spikes lasting about 1 s. The volleys, clustered in threes and fours, start off at low amplitudes, rise to a peak and then subside. The largest amplitude attained in this particular sequence is about 5–6 mV. Both upward and downward spikes are present. The loud volleys are sustained for nearly one minute. A contracted time scale in the bottom frame illustrates the larger pattern, which bears a fractal-like self-similarity relationship to the pattern in the expanded time scale. One minute of volleys, alternates with one minute of relative silence, and groups of three successive volleys are separated by longer periods of silences. Note also the shift in base lines that accompany each volley of activity.

Figure 6 contains successively later frames of a posterior pole recording between 42 m 40 s and 52 mm 44 s of development, coinciding with the period of mass nuclear migrations. This trace starts with the typical pattern of activities: clusters of 2, 3, or 4 volleys, each lasting about 1 to 2 s, punctuated

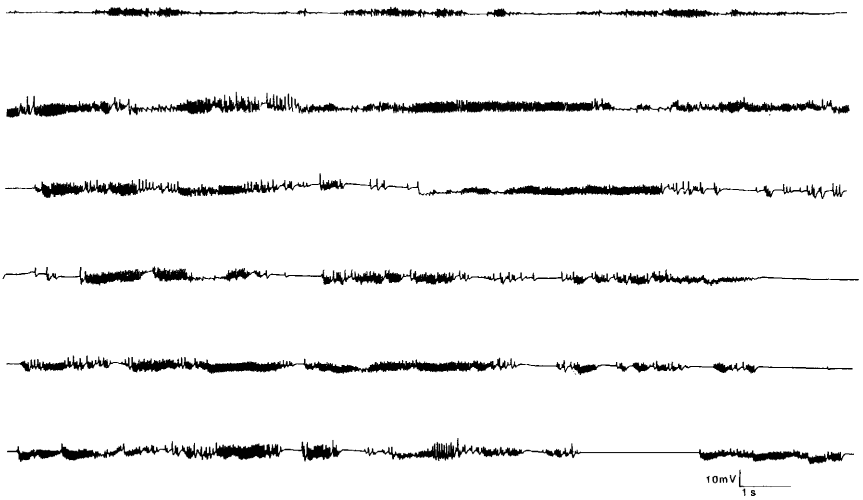

Fig. 6. Successive frames from a continuous recording at the posterior polar pocket during nuclear migration stages. (See text for details.)

by 2–3 s of quietude. The volleys increase in amplitude and tend to coalesce into a continuous train. The peak amplitudes are about 10–12 mV. Once again, we see the periodic shifts in baseline potential underneath the spiking activities, often coinciding with the start and end of each volley. The highest frequency of the spikes are about 30 hz but can be as low as 15 or even 5.

b. Discussion

The electrical activities of the early embryo consist of action potentials superimposed on periodic abrupt changes in field potential. They are consistent with the coherent excitations predicted by Frohlich (1980). The abrupt potential changes may reflect metastable polarizations of the embryonic field arising from the condensation and mode softening of electromechanical vibrations into a collective mode ($w \sim 0$) which can undergo limit-cycle oscillations. In turn, they trigger ion-channel activities reflected in the cluster of action potential-like discharges, which have their own collective modes (15 hz). All these activities occur during the period of pattern determination and are most intimately associated with it, as shown by the embryos' extreme sensitivity to external magnetic fields within the same period of time.

3. Biophoton Emission

This work is reported in detail elsewhere (Ho et al., 1991b). Both self-emission and short-term rescattering of light undergo the most dramatic changes during pattern determination, suggesting that they can be used as non-invasive probes for the process. In the short-term rescattering of light (0.2 to 10 s after

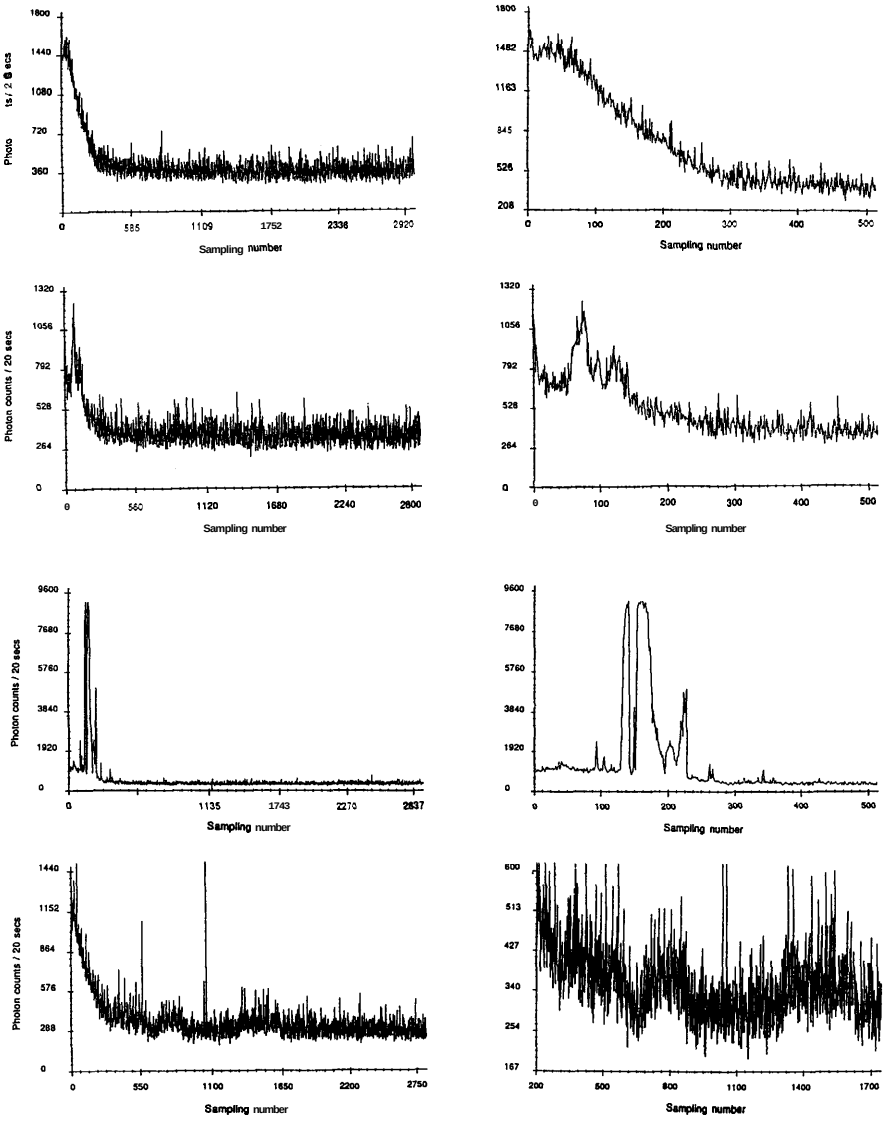

Fig. 7. Superdelayed luminescence in synchronously developing populations of Drosophila embryos. Top to bottom: control batch of 289 embryos not exposed to white light stimulation, exhibiting typical pattern of self-emission; batch of 107 embryos exposed to white light for one minute at 10 m of development; batch of 232 embryos exposed to white light at 5 m of development; batch of 172 embryos exposed to white light at 5 m of development. The traces on the right are expanded versions of those on the left.

exposure), we obtain probably the highest intensity for biomass of any system previously examined. The decay of rescattered light follows the hyperbolic kinetics found in all living systems, which, as argued by Popp (1986), is sufficient condition for coherence in the system investigated. In addition, we

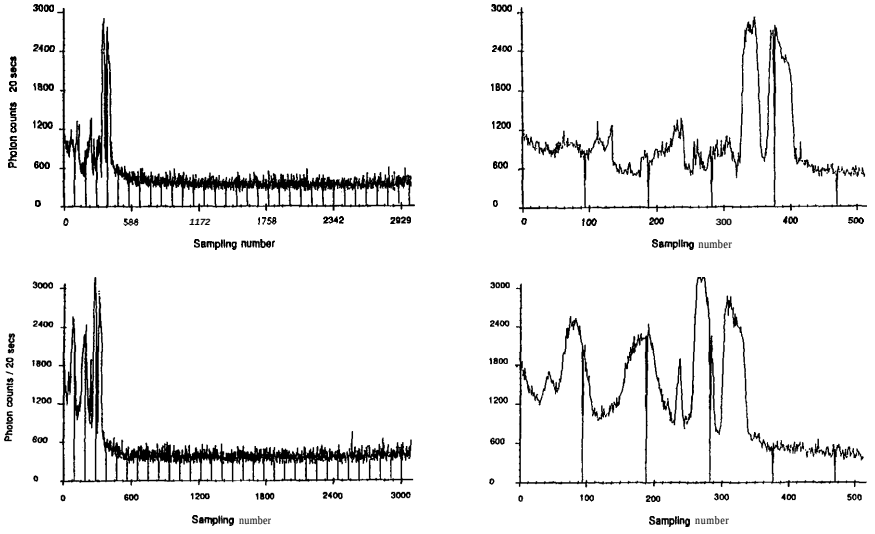

Fig. 8. Superdelayed luminescence unperturbed by periodic exposure to red light. Top, batch of 274 embryos exposed at 20 m of development; bottom, batch of 245 embryos exposed at 5 m of development. Five second pulses of red light were delivered 30 m apart during the entire period of measurement.

discovered the most remarkable new phenomenon of superdelayed luminescent flashes, which we shall describe here.

a. Superdelayed Luminescent Flashes

When the embryos are stimulated by exposure to white light (4 W/m^2) for 1 minute within the first 40 minutes of development, a new kind of luminescence makes its appearance in the form of superdelayed, intense flashes. The delay time for the first flash varies from 1 minute for single sharp bursts (duration $<$ 1 second), to about 20 minutes for sustained bursts ($>$ 20 seconds). Multiple flashes typically appear; and either follow in quick succession

TABLE 1
Parameters of superdelayed luminescence with multiple prolonged flashes

N	N^2	t_0	t_D	$t_{D(max)}$	P_e	P_{max}
172	29,584	7	20	186	47,504	750
107	11,449	10	20	20	19,362	582
232	53,824	5	31	45	356,000	8,160
245	60,025	5	20	92	259,168	2,000
274	75,076	20	57	132	205,479	2,100
159	25,281	15	34	128	87,556	2,800
100	10,000	10	10	35	5,743	1,000

N, number of embryos; t_0, developmental time at light exposure; t_D, delay time to first flash; $t_{D(max)}$, delay time to last flash; P_e, total superdelayed luminescence (photon count) in excess of baseline; P_{max}, maximum photon count achieved in the superdelayed luminescence.

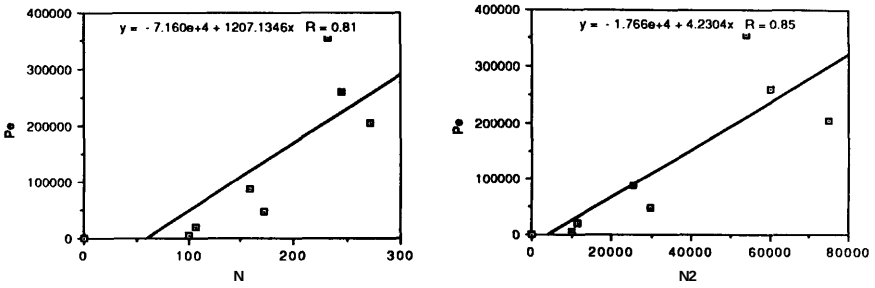

Fig. 9. Regression of P_e on N and N^2.

or after further delays, minutes or even hours apart. Each flash may be sustained for minutes to tens of minutes, and the longest delay time to the last flash is 8 hours (see Figure 7). These prolonged bursts are most dramatic; and are apparently unaffected by periodic 5 s pulses of red light stimulation (see Figure 8); indicating a remarkable degree of stability once the process has been initiated.

Certain conditions have to be satisfied for the observation of superdelayed luminescence:

1. The embryos must be synchronous to within 1 m at the start of development. Populations with asynchronous development, such as those containing more than 20% retained eggs or unfertilized eggs never exhibit any superdelayed luminescence.
2. The time at which white light stimulation is applied must fall within 40 minutes of the start of development.
3. The intensity and duration of light stimulation must not be less than about $4W/m^2$ for 60 seconds. Lights of limited spectral composition (red, green, or blue) were ineffective, or much less effective. But these may be because the intensity of light is lowered substantially by the filters used.
4. The embryos must be fairly evenly distributed over the inside of the quartz cuvette 5. The total number of embryos must be greater than 100.

Even given the above conditions, however, the multiple prolonged flashes do not always occur. Instead, either single flashes, or multiple sharp bursts may appear; or there may be no delayed flashes at all. In a total of 29 experiments where all the above conditions have been satisfied, 13 gave no flashes at all, 9 gave single flashes or multiple sharp bursts, and only 7 gave multiple prolonged flashes (see Table 1). At the moment, we still do no know whether uncontrolled geometrical factors such as the distribution of eggs in the cuvette and or other uncontrollable stochastic effects may be responsible for the variability.

The requirement for a minimum number of embryos may reflect a rela-

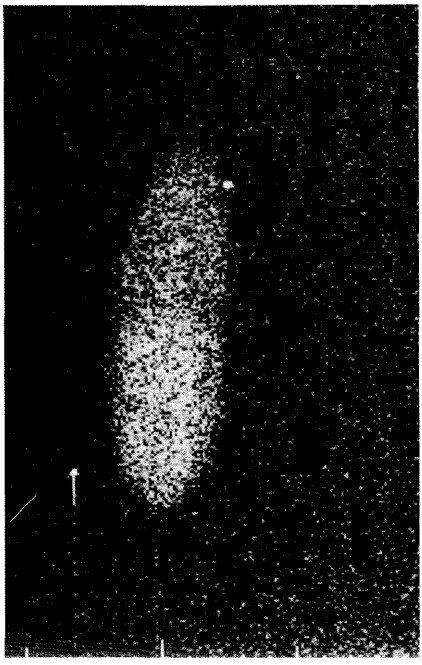

Fig. 10. Single *Drosophila* embryo imaged by its own superdelayed luminescence. The embryo was stimulated for scvcral minutes with light from the microscope at 10m of development, and the image was made up of light re-emitted bctwcen 15–20 m afterwards.

tionship between the total superdelayed re-emission, P,, (in excess of the self-emission background), and the number of embryos, N, which is suggested when one concentrated on all cases involving multiple prolonged flashes. There is a significant correlation between P_e and N or N^2, the correlation of N^2 being somewhat better than N (Figure 9); the correlation coefficient R, for N^2 is 0.85 vs 0.81 for N (significant at .O1 and .05 respectively) and the F value for the linear regression, 15.54 vs 11.51 (significant at .O1 and 0.025 respectively).

There does not seem to be any consistent relationship between the timing of individual flashes and the precise embryonic events occurring in the developing embryos, which clearly indicates that the flashes are not correlated with specific developmental or metabolic chemical events occurring at specific times.

The question arises as to whether single embryos may exhibit similar flashes, which only build up to the intense bursts recorded should many, if not all, of the embryos flash in synchrony. In preliminary experiments carried out in the laboratory of Astromed (Cambridge Science Park, Cambridge, U.K., with the kind assistance of Andrew Wilkinson and Rob Haggart), we have succeeded in obtaining an image of the single embryo 15 to 20 minutes after it

has been stimulated with the microscope light (Figure 10). This opens the way to imaging single embryos that has many important applications.

b. Discussion

We have demonstrated for the first time, a superdelayed luminescence that is dependent neither on detailed metabolic events nor on particular embryonic stages. Taken all together, the characteristics of superdelayed luminescence suggest that it is a cooperative phenomenon dependent on both synchrony within the population and some general physical state of the embryos within the first forty minutes of development. This is when nuclear divisions are occurring relatively rapidly and synchronously over the entire embryo, such that a high degree of global coherence may be inferred. The dependency of total superdelayed luminescence on N^2, the variable delay time, the forms of the flashes (particularly the multiple peaks of ringing effects), the dependence on geometry and the stochasticity and variability of the effect, are all reminiscent of the phenomenon of superradiance in a population of emitters which can interact nonlinearly to build up a coherent emission involving the whole population (see Gross and Haroche, 1982).

Drosophila females typically lay eggs just before sunrise, so the external light source may be used as an initial synchronizing signal *(Zeitgeber)* which maintains the circadian and other biological rhythms. The superdelayed re-emission could then be a means of maintaining communication and synchrony among individuals in the population. On the other hand, since the females do not deposit their eggs in nature in quite the same configuration as they are made to in our experiments, the effects we observe may simply be a consequence of our measurement conditions, and serve to inform us of the highly coherent state of the embryos at the time when light stimulation is applied. They indicate that synchronously developing embryos can interact nonlinearly to generate light emission which are coherent over the entire population, and often orders of magnitude higher than the self-emission rate.

These and other experiments (Ho et al., 1991b) demonstrate that photon-emission can be used to probe the physical state of the embryo during pattern determination which cannot be accessed by conventional biochemical or molecular biological means. We have barely scratched the surface of this fascinating area, and a lot more research needs to be done. Nevertheless, our observations already strongly suggest that the embryonic field is a physically coherent domain which not only gives global order to the embryo but enables them to interact cooperatively with other embryos, giving us new insights into the sociality that is at the basis of all life (see Ho, 1991 and references therein).

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