

Multiple Paths to Encephalization and Technical Civilizations

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Abstract We propose consideration of at least two possible evolutionary paths for the emergence of intelligent life with the potential for technical civilization. The first is the path via encephalization of homeothermic animals; the second is the path to swarm intelligence of so-called superorganisms, in particular the social insects. The path to each appears to be facilitated by environmental change: homeothermic animals by decreased climatic temperature and for swarm intelligence by increased oxygen levels.

Keywords Biosphere · Encephalization · Temperature · Oxygen · Social insects · Superorganism

Introduction

The subtext of the astrobiology research program is a working hypothesis that biologic and biospheric evolution are coarsely deterministic and that from similar initial conditions, “playing the tape again” should yield similar results. Thus, the observational search for alien biospheres will include looking for the possible presence of oxygen, water and methane biosignatures in the atmospheres of Earth-like planets around Sun-like stars in the coming decades, with the expectation that oxygenic photosynthesis and methanogenesis has commonly emerged in the metabolic history of alien biospheres. Similarly the SETI program implicitly assumes the probable emergence of intelligent civilizations capable of sending electromagnetic signals.

An outline of quasi-deterministic biospheric evolution has been previously proposed (Schwartzman 1999, 2002; Schwartzman 2008). The general pattern of the tightly coupled evolution of biota and climate on Earth has been the very probable outcome from a relatively small number of possible histories at the macroscale, given the same initial conditions. Major events in biotic evolution on our planet have included anoxygenic and oxygenic photosynthesis, the emergence of new cell types (eukaryotes) from the merging of

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complementary metabolisms, multicellularity (simple and complex), and encephalization. Changes in surface temperature, free oxygen and carbon dioxide levels resulting from the coevolution of life and its environment were constraints and triggers for these innovations.

Discussion

We propose two potential physiologically different paths for the emergence of intelligent life on Earth-like planets around Sun-like stars. The first path is constrained by climatic temperature. The long-term cooling history of the Earth's biosphere correlates with the timing of major events in biotic evolution, e.g., the emergence of phototrophs, eucaryotes and Metazoa apparently occurred when temperatures reached their maximum tolerable values for these organisms, i.e., 70°C (3.5 Ga), 60°C (2.8 Ga) and 50°C (1–1.5 Ga) respectively (Schwartzman 1999, 2002). This temperature scenario with a very warm early climate was recently reinforced by the measurement of melting temperatures of proteins resurrected from sequences inferred from robust molecular phylogenies Gaucher et al. 2008) as well as analysis of rRNA and protein sequences (Boussau et al. 2008), results consistent with the paleotemperatures derived from the oxygen isotopic record of ancient cherts (Knauth 2005; Schwartzman and Knauth 2009).

We proposed that the emergence of vertebrates and their encephalization likewise was similarly constrained by temperature (Schwartzman and Middendorf 2000; Schwartzman et al. 2009). Given an upper temperature limit for vertebrate growth, indeed homeothermic animals, is about 10°C below the limit for Metazoa, the surface temperature history of the biosphere suggests an even narrower window exists for maximum encephalization, roughly 500 million years ago through the present when climatic cooling became sufficient to allow additional and efficient heat loss from the large energy-intensive brain resulting from the burst in encephalization. During this period, encephalization is observed in hominid evolution, as well as for other groups of homeothermic animals including birds and toothed whales in the Cenozoic, and perhaps even for the mammal-like “reptiles” in the Permo-Carboniferous.

We derived a first approximation estimate of the cooling required for hominin brain size increase from a simple model of heat loss (Schwartzman et al. 2009). The result was rather modest cooling corresponding to 1–2°C, quite compatible with regional cooling during glacial episodes in the Pleistocene. We suggest that fire and cooking combined with climate to release brain size constraints. If climatic cooling was indeed a releaser for bigger brains, it may well have had a synergistic effect, i.e., colder nights would have favored more fire use with greater opportunities for cooking, thereby providing more easily digestible food. As Wrangham (2009) noted, this may have then freed energy for the brain, allowed for a reduction in jaw size and concomitant increase in other areas of the skull. The critical overheating challenge for bigger brains came during periods of diurnal activity, especially during the heat of the day if our ancestors were so compelled to obtain food then. So with onset of a glacial epoch or migration to higher elevations colder nights should have required fires to keep warm, while temperatures during activity were low enough for bigger brains to emerge, even with some pre-adaptations for cooling such as sweating and the cranial radiator, both plausibly present in the proximate ancestor to Homo.

The second path suggests a different constraint, sufficient oxygen levels in the atmosphere. Insect gigantism has been noted at times of elevated atmospheric oxygen levels, especially during the Carboniferous, the time of huge burial of organic carbon that was transformed into coal (Graham et al. 1995; Dudley 1998; Berner et al. 2007). Insect

physiology entails the diffusion of oxygen through their tracheal system, thus gigantism, especially for flying insects, imposes an oxygen demand likely only satisfied by higher ambient levels. While bigger insect brains are likely correlated with bigger bodies in general (Chittka and Niven 2009), it is recognized that mushroom bodies in the insect brain (there are two in each brain) function as the higher processing centers, particularly for those insects with generalist feeding habits (Farris 2008). Remarkable structural, functional and developmental convergence between insect mushroom bodies and the higher brain centers of vertebrates is noted (Farris and Roberts 2005). In the Carboniferous the evolutionary radiation of diverse orders of insects including the common ancestor of modern cockroaches and termites (Hoy 2008) resulted in the emergence of diverse mushroom body structures (Farris 2005; Strausfeld et al. 2009), the necessary condition for the evolution of social insects. Was the Carboniferous rise of atmospheric oxygen a trigger for these evolutionary developments, along with insect gigantism?

Thus, an outstanding question is whether there is an atmospheric oxygen level for insect encephalization that is analogous to the climatic temperature constraint for warm-blooded animals? Did the insect giants of the Carboniferous show a burst of encephalization analogous to that of homeothermic animals? And on a note of wild speculation, is the emergence of the collective superorganism intelligence of social insects (Gordon 1999; Hölldobler and Wilson 2008) the product of millions of individually communicating brains, in some colonies, linked to climatic changes? Should we humbly view the marvelous attine ant and termite fungal agriculture and the functional architecture of the termite mound (Turner 2000) the technology of this superorganism, as the analog of the human technosphere?

Further, is there even potential for the evolutionary emergence of a self-conscious brain, even a community of such individuals, from the colonies of social insects? For instance, could the clumping behavior of fire ant colonies in flooding episodes (Mlot et al. 2011; see e.g., Fig. 1) or bivouacking by army ants (Schnierla 1934) potentially evolve as a basis for physically connected social insects as the substrate of a self-consciousness brain? We note the number of neurons per individual ant is on the order of 3×10^5 (number of neurons in 2 mushroom bodies/social Hymenoptera, Farris and Roberts 2005; Chittka and Niven 2009 cite two references noting that a honeybee's brain having slightly less than 10^6 neurons).

Fig. 1 Fire Ant Raft - *Solenopsis invicta*, Kissimmee Prairie Preserve State Park, Florida, USA, Taken June 4, 2005, Size: about 1 ft in diameter



With single ant colonies documented up to 20×10^7 individuals (Beckers et al. 1989), the total number of neurons in an ant colony could certainly approach if not exceed that of a human brain with its approximately 10^{11} neurons. An electrically and chemically connected colony could emerge as a Collective Ant Brain (CAB). Of course, chemically facilitated communication between ants via pheromones is well known, and electrical communication has been already found in social insects (Galushko et al. 2004). We note that the largest ant supercolony size approaches 3×10^8 individuals (Hölldobler and Wilson 1990, citing Higashi and Yamauchi's (1979) estimate of a *Formica yessensis* supercolony comprised of 45,000 nests. Thus, potentially such a supercolony could link up a thousand CABs—each with human size neuron capacity.

Thus, could the collective intelligence observed in social insects be the second path to technical civilizations? Can we expect to eventually find insectoid civilizations on some Earth-like planets around sun-like stars?

References

- Beckers R, Goss S, Deneubourg JL, Pasteels JM (1989) Colony size, communication, and ant foraging strategy. *Psyche* 96:239–256
- Berner RA, VandenBrooks JM, Ward PD (2007) Oxygen and evolution. *Science* 316:557–558
- Boussau B, Blanquart S, Necsulea A, Lartillot N, Gouy M (2008) Parallel adaptations to high temperatures in the Archaean eon. *Nature* 456:942–945
- Chittka L, Niven J (2009) Are bigger brains better? *Curr Biol* 19:R995–R1008
- Dudley R (1998) Atmospheric oxygen, giant Paleozoic insects and the evolution of aerial locomotor performance. *J Exp Biol* 201:1043–1050
- Farris SM (2005) Evolution of insect mushroom bodies: old clues, new insights. *Arthropod Struct Dev* 34:211–234
- Farris SM (2008) Structural, functional and developmental convergence of the insect mushroom bodies with higher brain centers of vertebrates. *Brain Behav Evol* 72:1–15
- Farris SM, Roberts NS (2005) Coevolution of generalist feeding ecologies and gyrencephalic mushroom bodies in insects. *Proc Natl Acad Sci USA* 102(48):17394–17399
- Galushko DV, Natalya Y, Ermakov NY, Bergman DJ, Ishay JS (2004) Communication by electrical means in social insects. *Physiol Chem Phys Med NMR* 36(2):131–141
- Gaucher EA, Govindarajan S, Ganesh OK (2008) Paleotemperature trend for Precambrian life inferred from resurrected proteins. *Nature* 451:704–708
- Gordon D (1999) *Ants at work. How an insect society is organized*. The Free Press, New York
- Graham JB, Dudley R, Aguilar N, Gans C (1995) Implications of the late Palaeozoic oxygen pulse for physiology and evolution. *Nature* 375:117–120
- Higashi S, Yamauchi K (1979) Influence of a supercolonial ant *Formica (Formica) yessensis* Forel on the distribution of other ants in Ishikari Coast. *Jap J Ecol* 29(3):257–264
- Hölldobler B, Wilson EO (1990) *The ants*. Belknap, Cambridge
- Hölldobler B, Wilson EO (2008) *The superorganism the beauty, elegance, and strangeness of insect societies*. Norton, New York
- Hoy MA (2008) Fossil record of insects. In: Capinera JL (ed) *Encyclopedia of Entomology*. Springer. 1522–1524
- Knauth LP (2005) Temperature and salinity history of the Precambrian ocean: implications for the course of microbial evolution. *Palaeogeogr Palaeoclimatol Palaeoecol* 219:53–69
- Mlot NJ, Tovey CA, Hu DL (2011) Fire ants self-assemble waterproof rafts to survive floods. *Proc Natl Acad Sci USA* 108:7669–7673
- Schnierla TC (1934) Raiding and other outstanding phenomena in the behavior of army ants. *Proc Natl Acad Sci USA* 20:316–321
- Schwartzman D (1999, 2002) *Life, temperature, and the earth: the self-organizing biosphere*. Columbia University Press, New York
- Schwartzman DW (2008) Coevolution of the biosphere and climate. In: Jorgensen SE, Fath B (eds) *Encyclopedia of Ecology*, 1st edn. Elsevier B.V, Oxford, pp 648–658

- Schwartzman D, Middendorf G (2000) Biospheric cooling and the emergence of intelligence. In: Lemarchand GA, Meech KJ (eds.) *A New Era in Bioastronomy*, ASP Conference Series, Vol. 213, pp. 425–429
- Schwartzman DW, Knauth LP (2009) A hot climate on early Earth: implications to biospheric evolution. In: Meech KJ, Keane JV, Mumma MJ, Siefert JL, Werthimer DJ (eds) *Bioastronomy 2007: Molecules, Microbes, and Extraterrestrial Life*, Astronomical Society of the Pacific Conference Series Vol. 420, San Francisco, pp. 221–228
- Schwartzman D, Middendorf M, Armour-Chelu M (2009) Was climate the prime releaser for encephalization? An editorial comment. *Climatic change* 95. Issue 3:439–447
- Strausfeld NJ, Sinakevitch I, Brown SM, Farris SM (2009) Ground Plan of the Insect Mushroom Body: Functional and Evolutionary Implications. *J Comp Neurol* 513:265–291
- Turner JS (2000) *The extended organism: the physiology of animal-built structures*. Harvard University Press, Cambridge
- Wrangham R (2009) *Catching fire: how cooking made us human*. Basic Books, New York