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Emergent pattern dynamics in reaction-diffusion-convection system

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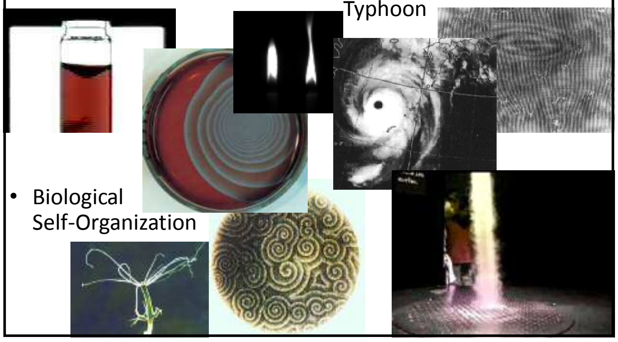
Contents

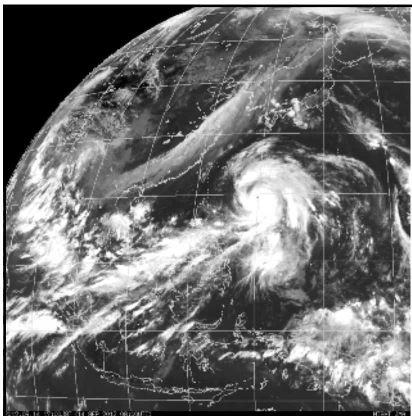
Key Words: SYNC, Convection Oscillator, Flow Waves

1. Introduction: Emerging Phenomena

Emerging Phenomena in Nature

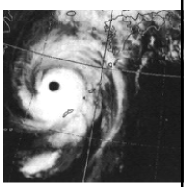
- Chemical Reaction
- Convection, Tornado, Typhoon
- Biological Self-Organization





Hierarchical Pattern Dynamics Emerging in Reaction-Diffusion and Convection System

Typhoon Mirelle
Max imam Wind Speed:
88m/s (Kagoshima)
53.9m/s (Aomori)
940 hPa

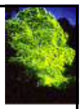


Typhoon 16(Samba), 2012.9.14 900hPa

Typhoon 19, 1991.9.27

SYNC: The Emerging Science of Spontaneous Order (2003)

Science on Synchrony in Nature



- Explaining spontaneous order in time and spatial-temporal self-organization at every scale from the nucleus to cosmos.
- All things in the universe does not obey the classical thermodynamics theory. We see the emergence of order as a victorious uphill battle against entropy.
- A great variety of synchrony in nature:

  Synchronal flashing of **fireflies**, cardiac arrhythmias, super-conductivity, sleep cycles, the stability of the power grid, ..
- Science: Synthetic & Integrated ← Analytic & Reductionistic

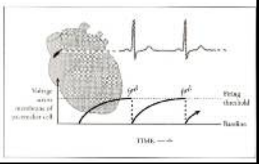
  1960s : **C**ybernetics

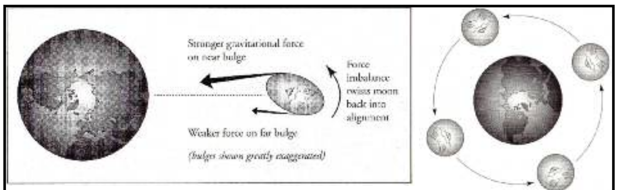
  1970s : **C**atastrophe

  1980s : **C**haos theory

  1990s : **C**omplexity theory

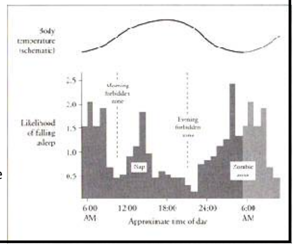
  2000s : Emerging Science (SYNC)





The synchronization between the moon's orbit and its spin: a 1:1 spin-orbit resonance, or tidal locking

A broad peak centered around the temperature trough coincide with the zombie zone, indicating that this window of minimum alertness was also the time of maximum sleepiness.



Great similarity between the sync of oscillators and the phase transition : emphasized point

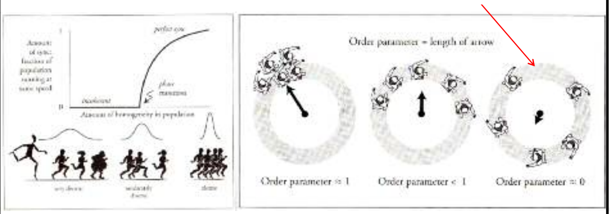
- A. Winfree discovered an unexpected link between biology and physics. He realized that mutual synchronization is analogous to a phase transition.

  ＝ Statistical physics can be a key to solve the great variety of synchrony in nature.
- Y. Kuramoto simplified Winfree's model and obtained the exact solution. The model revealed the essence of group synchronization.

Great similarity between the sync of oscillators and the phase transition

- Winfree's model: $\dot{\phi}_i = \omega_i + Z(\phi_i)I(t), \quad I(t) = \frac{K}{N}\sum_{j=1}^{N} V(\phi_j)$
- Kuramoto's model: $\dot{\phi}_i = \omega_i + \frac{K}{N}\sum_{j=1}^{N} \sin(\phi_j - \phi_i)$

Incoherent Equilibrium State



Important Points of SYNC

- Analogy between group synchronization and phase transition had been established.
- **S. Strogaze** proposed a concept of "Oscillator Fluid" to solve the stability problem of the incoherent equilibrium state. The answer was "**neutrally stable**".
- **Reductionism** may not be powerful enough to solve all the great mysteries we're facing: Cancer, Consciousness, The Origin of Life, AIDS, Global Warming, ･･･
- **Nonlinear dynamics** is central to the future of science.

  Chaos → Complexity → Emergence → What comes next？

2. Synchronization of Candle Flame Oscillators

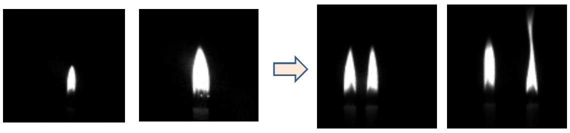
Candle Flame＝Nonlinear Oscillator

Oscillation of flame brightness（Ishida & Harada, in "Kagaku to Kyoushitsu", 1990）

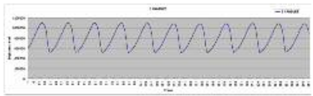
Oscillations and Synchronization in the Combustion of Candles, H. Kitahata et al., J. Phys. Chem, 113(2009), pp.8164-8168

Flame oscillations in a bundle of candles

Synchronization of flame oscillation



A candle flame | Flame oscillation of a bundle of candles | In-phase SYNC | Anti-phase synchronization



Nonlinear Oscillation of Flame Brightness

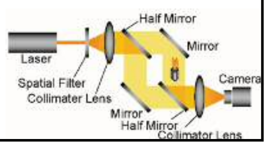
Oscillation and Synchronization in the Combustion of Candles

A research project with 10 scientists from 5 universities

- Expriments：
  - Chiba Univ.: H. Kitahata, T. Sakurai
  - Yamaguchi U.: J. Taguchi, A. Osa, H. Miike
  - Kyoto U.: Y. Sumino, M. Tanaka
- Modeling and Numerical Analysis：
  - Kanazawa U.: M. Nagayama, Y. Ikura
  - Gakushuuin U.: E. Yokoyama

J. Phys. Chem., 113 (2009)

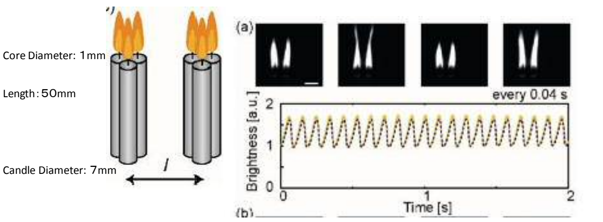
Visualization of flow structure by Mach-Zehnder interferometer



In-phase synchronization between two candle flame oscillators

- Close Distance Case: （l = 2～3cm）

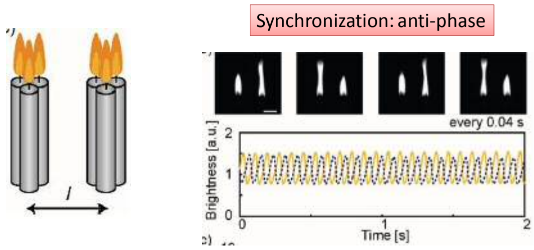
Synchronization: in-phase



Anti-phase synchronization between two candle flame oscillators

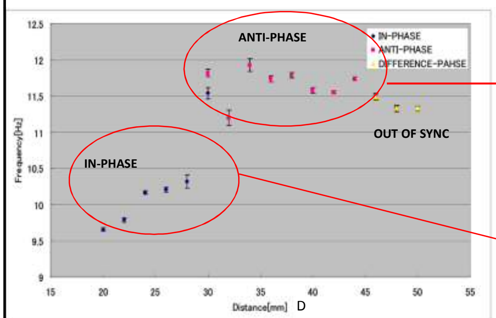
- Moderate Distance Case: （l = 3～5cm）

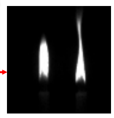
Synchronization: anti-phase



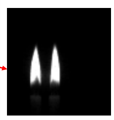
Depending on the distance parameter D Synchronization between two oscillators changes from **in-phase** to **anti- phase**.

→ What is the origin of the mutual correlation?





Anti-phase SYNC



In-phase SYNC

A model for candle flame oscillator

$$C\frac{dT_i}{dt} = \omega_1\left[h(T_0 - T_i) + \beta a n_i \exp\left(-\frac{E}{RT_i}\right)\right] + \sigma\left(\frac{\mu}{L^2}T_j^4 - T_i^4\right)$$

$$\frac{dn_i}{dt} = \omega_2\left[k(n_0 - n_i) - a n_i \exp\left(-\frac{E}{RT_i}\right)\right]$$

Interaction by radiation between two candles.

Flame oscillation caused by periodic oxygen lack by combustion.

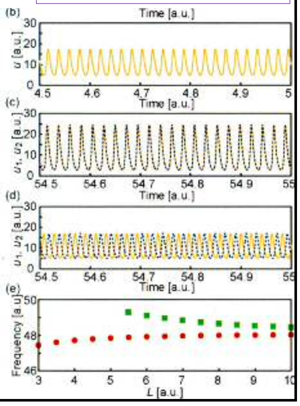
- a: Supply rate of paraffin
- C: Specific heat
- R: Gas constant
- E: Active energy
- T_0: External temperature
- n_0: External O_2 concentration
- ω_1: Time const. for T-change
- ω_2: Time const. for O_2-change
- h: Heat flow by convection
- k: Supply rate of oxygen by convection
- β: Heat production by combustion
- σ: Stefan-Boltzman Constant
- T_i, T_j: Temperature of the flame
- n_i, n_j: Concentration of oxygen
- $i, j = 1,2 (i \neq j)$

A mathematical model by M. Nagayama and Y. Ikura（Kanazawa University）

Problems of the model

- Temporal shape of the numerical oscillation is not coincide with the experiments（b).
- Difference in the coexisting region of in-phase sync and anti-phase one between the experiments and the model is recognized（e）.
- Mutual correlation caused by the thermal radiation is not directly confirmed by experiments.
- Convective flow（ascending current ）and turbulence caused by the flame are not directly taken into account in the model.

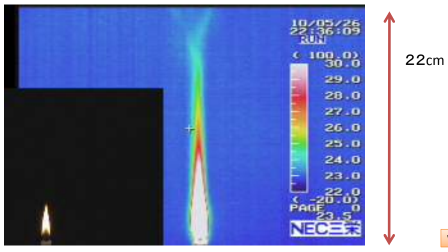
Results of the numerical analysis by the proposed model.



New observations by a thermal camera :

A flame oscillation by a bundle of two candles.

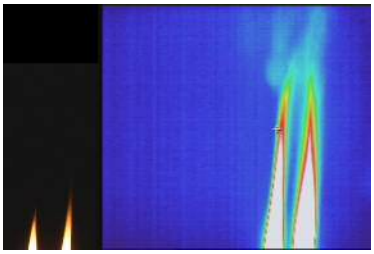
- An eddy like convection appeared over the candle flame.
- The oscillation began to start when the eddy touch down the candle flame.



New observations by a thermal camera:

In-phase sync of the flame oscillation appeared in two bundles of candles.

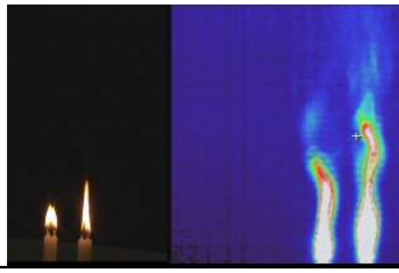
- When the bundled two candles arranged at a close position, the eddy currents curled up and developed into a big vortex of convection.



New observations by a thermal camera:

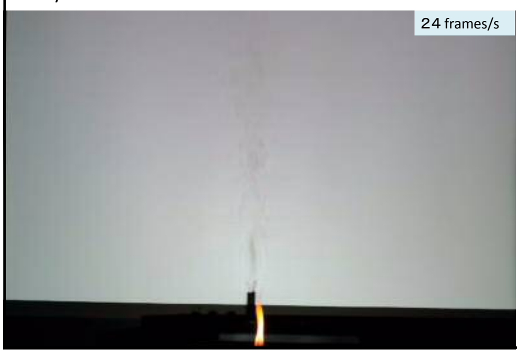
Anti-phase sync of the flame oscillation appeared in two bundles of candles.

- When the bundled two candles arranged at an apart position, the eddy currents did not curl up and stayed in two independent eddy like convections.



New Observations by High-speed Camera (300 frames/sec): Shadow Graph

Eddy like convection is confirmed over the candle flame.



Discussion

KH-instability

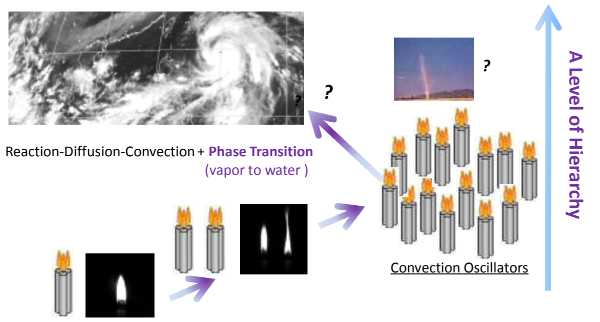
1. Candle flame oscillation is possibly caused not only by periodic oxygen lack with combustion but also by the eddy like convection appeared over the flame. The eddy structure can be originated by Kelvin-Helmholtz (KH) instability.
2. Synchronization between the flame oscillators can be induced by the interaction associated with the vortexes dynamics.

  ･Depending on distance of oscillators the synchrony changes from in-phase to anti-phase. The change can be caused by difference of the vortex dynamics.

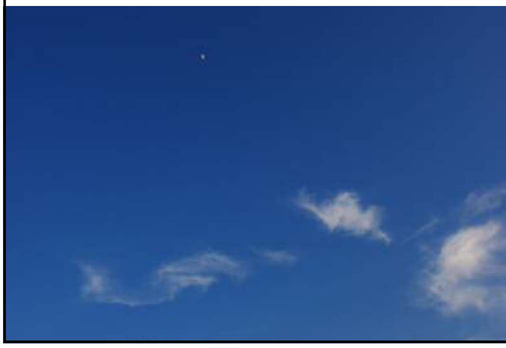
  In-phase (close)： A unified vortex is developed.
  Anti-phase (apart)： Two vortexes keep independence.

Hierarchical pattern dynamics in candle flame oscillators (CFO)

- What may happen in crowded CFO?



3. Understanding Flow Waves Dynamics in Belousov-Zhabotinsky Reaction



Chemical Rotors in *"When Time Breaks Down"* by Arthur T. Winfree

Reaction-Diffusion Model for BZ-reaction

- Oregonator Model (Tyson Version)

$$\frac{\partial u}{\partial t} = D_u \nabla^2 u + \frac{1}{\varepsilon}\{u(1-u) - fw\frac{u-q}{u+q}\}$$

$$\frac{\partial w}{\partial t} = D_w \nabla^2 w + (u-w)$$

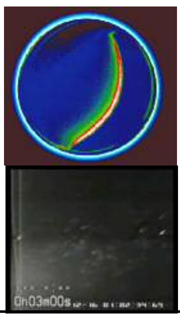
u : Activator w : Inhibitor

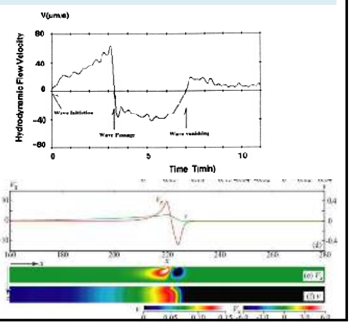
$D_u > D_w$: Diffusion Coefficient

$\varepsilon << 1$

(1) Flow oscillation induced by a chemical wave.

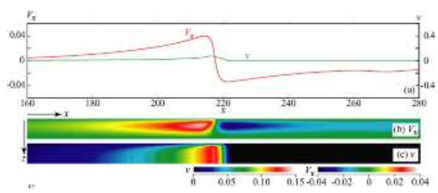
- A single chemical wave excited in BZ-solution induces convective flow change. This can be regarded as a forced oscillation caused by passage of the chemical wave.





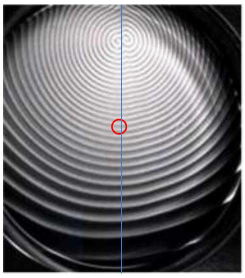
Many **reaction-diffusion-convection models** trying to explain convection associated with chemical waves

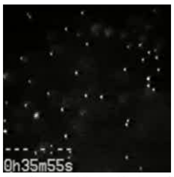
- 1995: H. Wilke, Physica D 86
- 1996: K. Matthiessen et al., Phys. Rev. E 53
- 1996: M. Diewald et al., Phys. Rev. Lett. 77
- 2002: H. Kitahata et al., J. Chem. Phys. 116

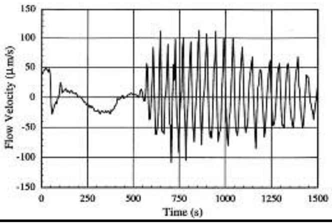


A. Nomura, 2005
Viscous-Elastic
Surface Model

（2）Oscillatory convection induced by chemical wave trains

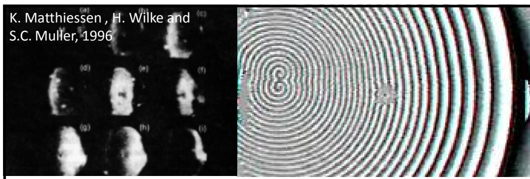






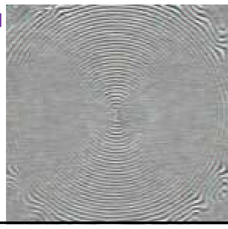
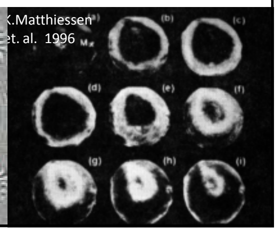
H.Miike et al., 1987.12.24

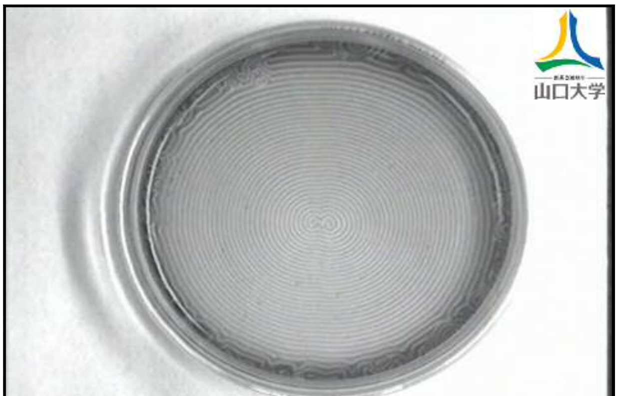
Self-Organized Oscillation of Convection in BZ-Solution Exciting Spiral Waves.



(3) Flow Waves (=global structure of the oscillatory convection) Observed in BZ-solution under Exciting Chemical Spiral Waves.

= Hierarchical Structures

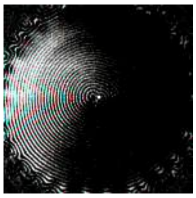


Emergence and Extinction of Order in Chemical Reaction:

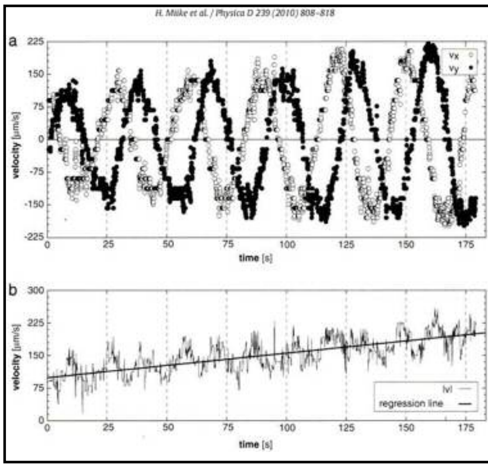
Spiral Flow Waves in Chemical Spiral Waves of BZ-Reaction, T. Sakurai et al., 2003

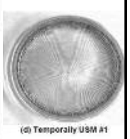
(4) Spiral Flow Waves of Hierarchical Pattern Dynamics Self-Organized in BZ-solution

- Direction of Hydrodynamic Flow is Rotating.
- Flow Waves of Spiral Shape is Rotating.
- Flow Waves
  = Global Synchrony of Distributed Nonlinear Convection Oscillators ?



T. Sakurai et al., J. Phys. Soc. Japan, 2003





H. Miike et al., Physica D, 2009

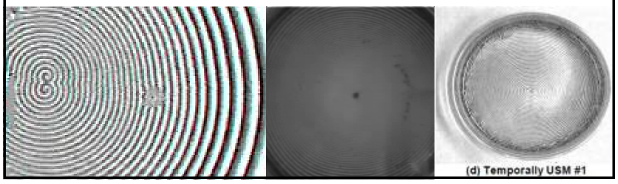
A New Scheme Understanding Oscillatory Convection and Flow Waves

- A local convective oscillation is induced by the passage of chemical wave trains.
- The oscillation period changes by the decrement of wavelength of the wave trains.
  - → Periodic passage of chemical wave＝Forced oscillation
  - → A periodic distribution of **convection oscillators** is formed.
- Development of chemical wave makes a coherent structure.
  - → Frequency distribution of the oscillators becomes sharp.
  - → A synchronization of the **convection oscillators** appears.
  - ＝ Flow Waves(Oscillatory Convection)

A new scheme:
＝Understanding flow waves as the sync of **convection oscillators**

Unsolved characteristics expected to understand by introducing the new scheme.

- Frequency of the flow wave's oscillation or rotation.
- Wavelength or scale of flow wave.
- Direction of flow wave propagation.
- Birth, growth and death of flow waves.



4. Concluding Remarks

Flow Waves = Hierarchical pattern dynamics

- Spiral flow wave can be a hierarchical pattern dynamics associated with synchrony of the convection oscillators.
- The convection oscillators are self-organized in a BZ-solution layer having **coherent structure** of chemical wave trains.

1. Excitation of chemical spiral wave trains in a BZ-solution.
2. Establishment of a coherent structure of the wave trains:
3. Induction of flow waves after establishment of the coherent structure: **Birth**
5. Development of flow waves with time: **Growth**
6. Destruction of chemical wave by the developed convection: **Death**

→ How to simulate the evanescence (birth, growth and death) of nature?

Thank you for your kind attention.