Why evolution?

Why the Stars and the Universe Evolve?

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Jan 10, 2011

Wärmetod or Emergence of structures?

- R. Clausius: Thermal death of the universe (1865)
- In reality: Full of diversities (structures)
- Initially non-(thermal) equilibrium ?

  - Who gave such information initially? God?
- Contrary, 3K bkgd radiation tells initially almost in eql:

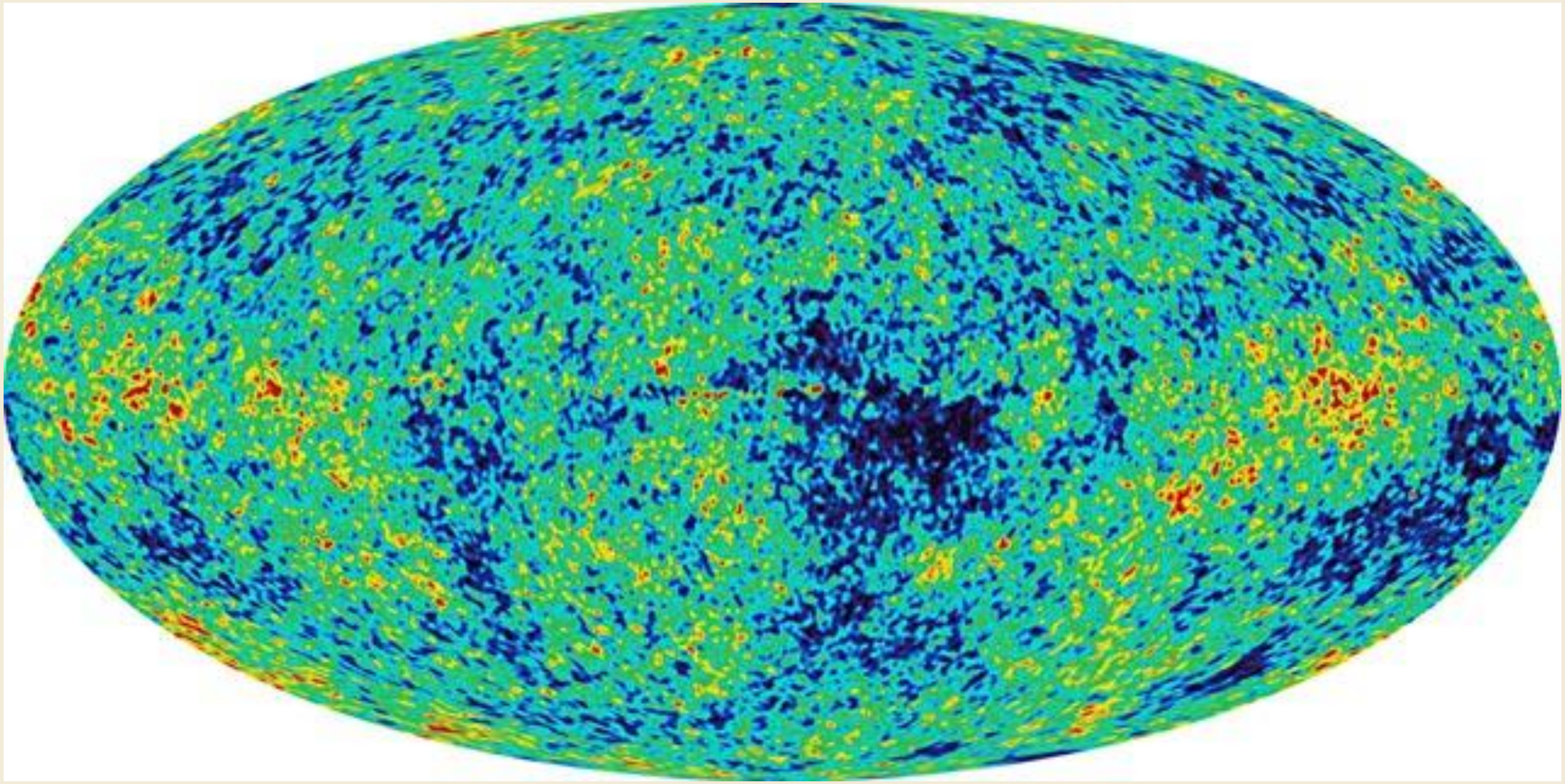
  - extent of its fluctuation is only 1/100000

  - requires emergence of orders (information)
- What are the mechanisms to generate structures and information of such a great extent (contrast)
- There are two important mechanisms

Wilkinson Microwave Anisotropy Probe

WMAP : by NASA

10^{-5}



The first mechanism

- Boundary Conditions to the system change

  - Universe expanded more rapidly than recovering therm. eql.

    -- time scales: expansion << relaxation in early Univ

  - NSE composition: H (high T) / He / Fe (low T)

    -- temp dropped before the nuclear eql re-established

    i.e., dropping-out (falling-behind) of changing thermal eql

- Other examples:

  - earth's atmosphere out of therm eql

    -- ascending current is rapid

  - (in industry) fractional distillation of crude oil

The second mechanism
-- effects of gravity (gravothermodyn)

- Forming core-halo structures

  - in density and/or temperature distributions:

    celestial obj / thin space, clustering of obj's,

    stellar core / halo, the sun / the planets

  - in specific angular momentum distr:

    galactic core / spiral arm, the sun / the planetary sys

- Mechanism: Coupling between gravity and thermal effects (kinetic energy – pressure)

Simple example: Virial Theorem

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{GM_r\rho}{r^2} \quad \Longrightarrow \quad \int_0^R \frac{\mathrm{d}P}{\mathrm{d}r} 4\pi r^3 \mathrm{d}r = -\int_0^R \frac{GM_r\rho}{r^2} 4\pi r^3 \mathrm{d}r$$

partial integr & BC with $P = (\gamma - 1)\rho u$

$$3(\gamma - 1)\int_0^M u\,dM_r - \int_0^M \frac{GM_r}{r} dM_r = 0$$

$$2E_{\mathrm{th}} + E_{\mathrm{gr}} = 0 \quad \text{for} \quad (\gamma = 5/3)$$

$$E_{\mathrm{tot}} = E_{\mathrm{gr}} + E_{\mathrm{th}} = -E_{\mathrm{th}} < 0$$

$$L = -\frac{dE_{\mathrm{tot}}}{dt} = \frac{dE_{\mathrm{th}}}{dt} > 0$$

Temperature rises
when energy (entropy) dumped away
- negative (effective) specific heat

Gravothermal catastrophe

- В.А. Антонов, 1962, Вест. Ленингр. Госдр. Унив.
- D. Lynden-Bell & R. Wood, 1968, MN (turn pt of lin series)
- I.Hashisu & D.Sugimoto, 1978, PTP

  normal-mode method
- I.H., Y.Nakada, K.Nomoto & D.S., 1978, PTP

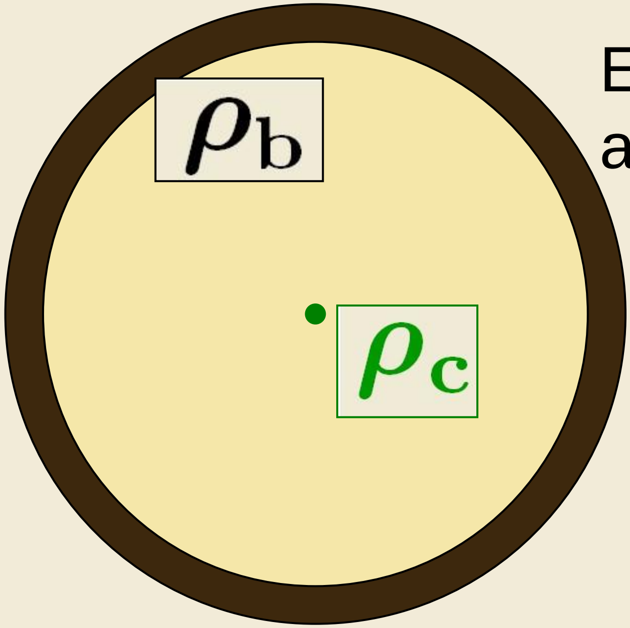
  catastrophe of finite amplitude = grav. contr.
- D.S., Y.Eriguchi & I.H., 1981, PTP Suppl.

  summary and extension to cosmology

  - easy understandings of stellar structure & evolution

  - resolved the problem of thermal death of the univ

gravothermal catastrophe
(isothermal gas sphere)

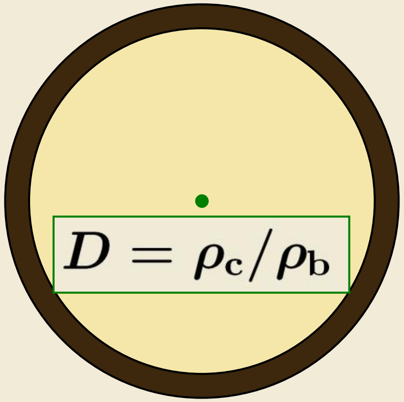


Enclosed by adiabatic wall

density contrast

$$D \equiv \frac{\rho_{\rm c}}{\rho_{\rm b}} > 1$$

Redistribution of specific entropy



Removal of heat (specific entropy)

$$\delta q = T\delta s < 0$$

$$\delta T = \frac{\delta q}{c} + (\delta T)_{\mathrm{comp/exp}} = \frac{\delta q}{c^*}$$

Change due to resulting compression

$$(\delta T)_{\mathrm{comp/exp}} > 0$$

Combined result can be $$\frac{\delta q}{c^*} < 0$$

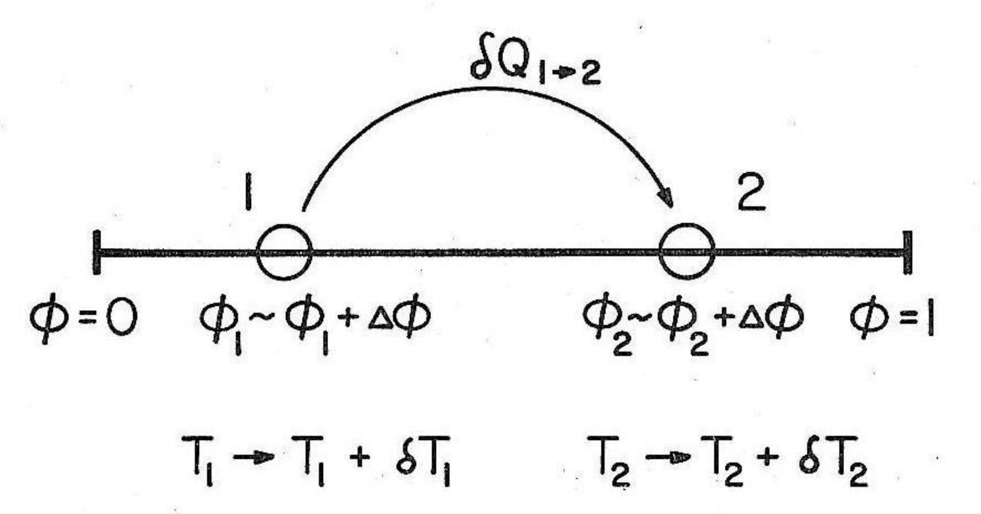
c* : gravothermal specific heat

- When D<709 : c* > 0, i.e., thermal state
- When D>709 : c* < 0, i.e., gravothermal state

↑ negative specific heat

leading to thermodynamic instability

Negative specific heat leads to thermal instability



first order:

$$\delta S = \left(\frac{1}{T_2} - \frac{1}{T_1}\right)\delta Q_{1\to 2} = 0$$

for initially isothermal case

second order:

$$\delta^2 S = \left(\frac{1}{T_0+\delta T_2/2} - \frac{1}{T_0+\delta T_1/2}\right)\delta Q_{1\to 2} = \frac{1}{2T_0}\left(\frac{\delta T_1}{T_0} - \frac{\delta T_2}{T_0}\right)\delta Q_{1\to 2}. \quad > 0$$

for $\delta T_1 > \delta T_2$ (for negative specific heat)

i.e., entropy production (unstable)

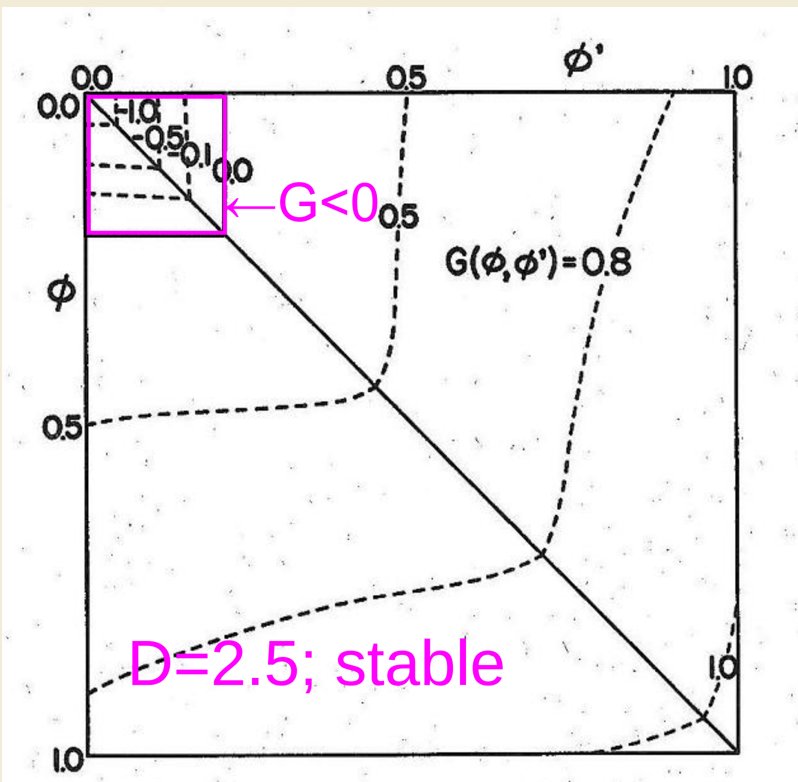
→ Temp gradient spontaneously appears

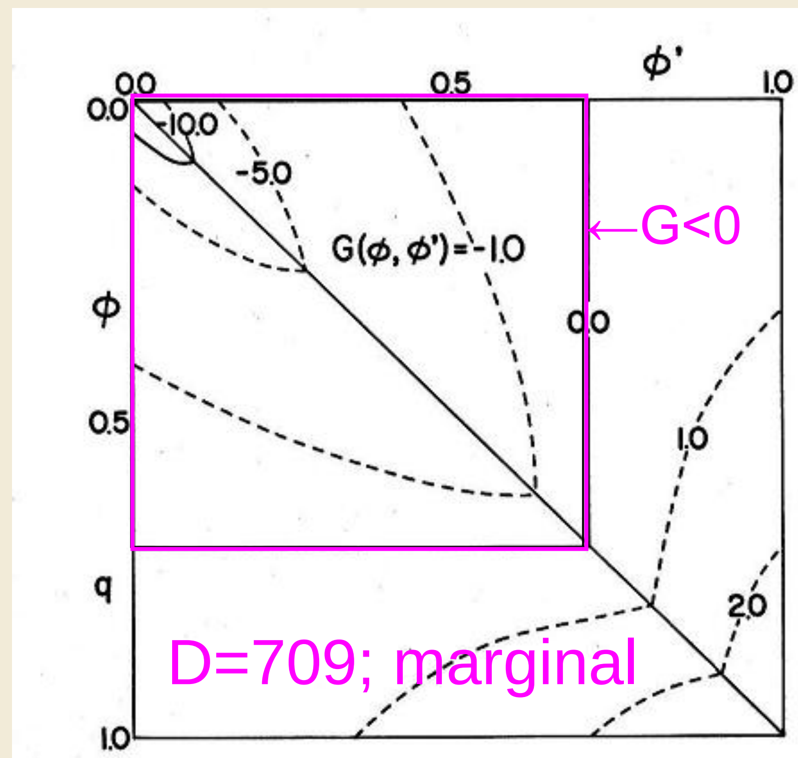
inverse
(gravothermal)
tensor
specific heat

$$\delta \ln P = \int_0^1 G(\phi, \phi')\delta\sigma(\phi')d\phi'$$

$$\delta \ln T = \int_0^1 F(\phi, \phi')\delta\sigma(\phi')d\phi'$$

$$F(\phi, \phi') = \frac{2}{5}[G(\phi, \phi') + \delta(\phi - \phi')]$$



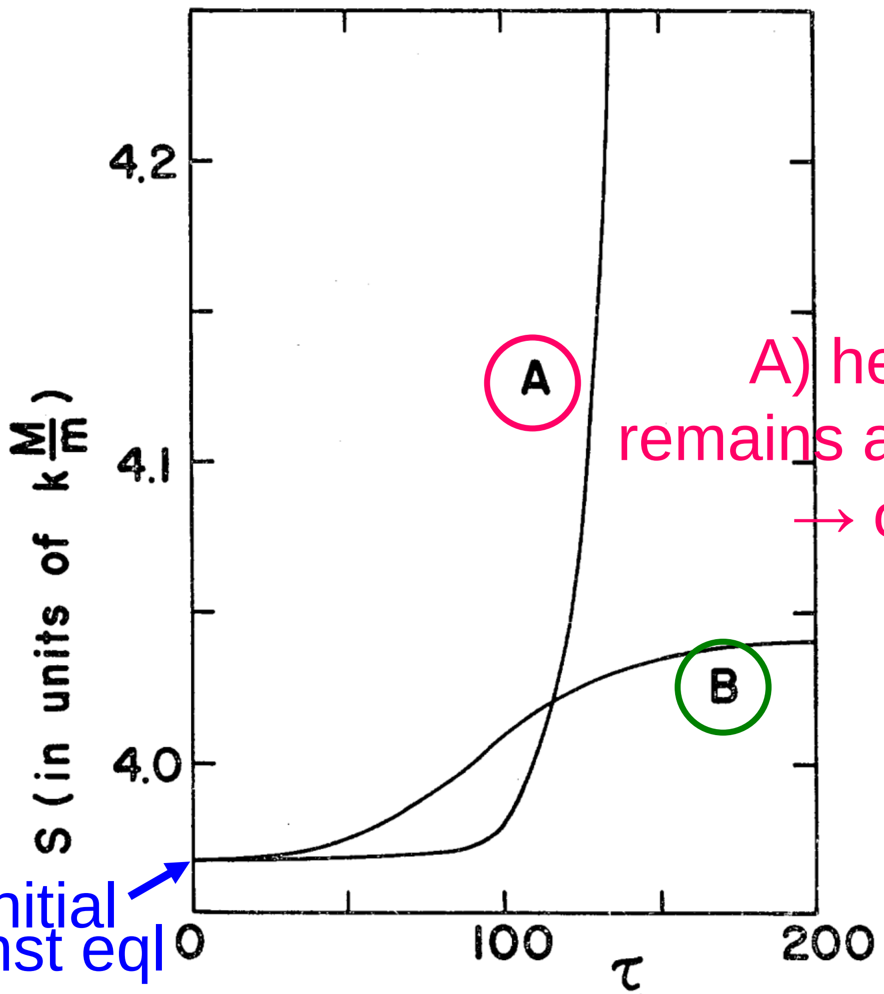


I.Hashisu & D.Sugimoto, 1978, PTP

Fundamental reason

phenomena:	energy	common sense of thermodynamics?
▪ surface tension:	$M^{2/3}$ (sub-extensive)	along
▪ general cases:	M^{1} (extensive)	along
▪ gravitational:	M^{2} (super-extensive)	out of

coming fm: self energy $\leftarrow \infty$ effective range



initial
unst eql

Fig. 5. Changes in the total entropy of the system for the cases A and B.

Two cases A) & B)
of evolution for different
initial perturbations

A) heat outwards
remains as gravoth system
→ catastrophe

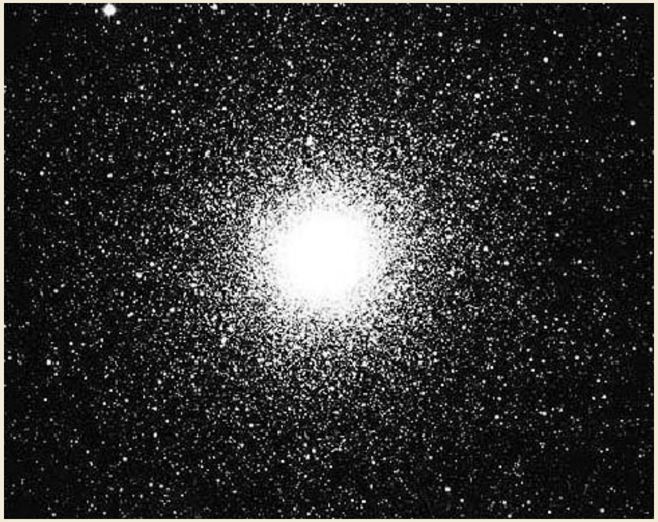
B) heat inwards
towards thermal system
→another stable eql

I.Hashisu,Y.Nakada,K.Nomoto & D.Sugimoto, 1978,PThPh,60,393

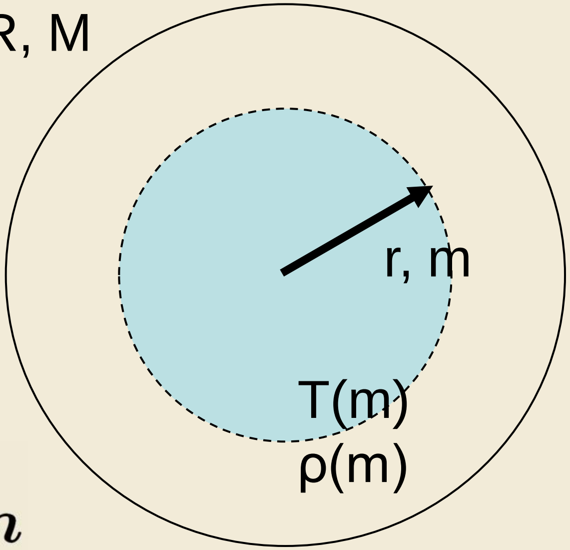
Fate of Evolution

Initially in Gravothermal state
evolution triggered by
(A) outward heat flow
→ core contr vs halo exp
→ T and ρ gradients more enhanced
→ higher D → more gravothermal
→ $\rho_c \to \infty$ in a finite time, (catastrophe)
(B) inward heat flow
→ core exp & halo cotntr
→ lower D → less gravothermal
→ isothermal state
(another thermal state with higher S)

Applied for open system



- A globular star cluster
  Gravitational N-(many-) body problem:
  Each star represented by a point-mass
  gravitationally interacting each other.



- Stellar Interior
  T & ρ distributions
  as fns of Lagrangian co-ordinate ***m***

In both cases: $\boldsymbol{S} = \int_0^M \boldsymbol{s(m)}\mathrm{d}\boldsymbol{m}$

Entropy Aspect of the System

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \left(\frac{\mathrm{d}S}{\mathrm{d}t}\right)_{\mathrm{in}} - \left(\frac{\mathrm{d}S}{\mathrm{d}t}\right)_{\mathrm{out}} + \left(\frac{\mathrm{d}S}{\mathrm{d}t}\right)_{\mathrm{irr}}$$

Open system (Stellar interior / Earth atmos / Life =metabolism)

*in*put fm (Ln / solar rad / food)

out to (stellar light / IR rad / heat & elimination)

irr: entropy production by heat transport etc

- (secular) cooling (grav contraction): no input & *S* decreasing
- Steady state $\frac{\mathrm{d}S}{\mathrm{d}t} = 0$ (nuclear burning phase)
- (rapid) thermodyn transition

  $\left(\frac{\mathrm{d}S}{\mathrm{d}t}\right)_{\mathrm{out}}$ small as comp'd with other terms (flash etc)

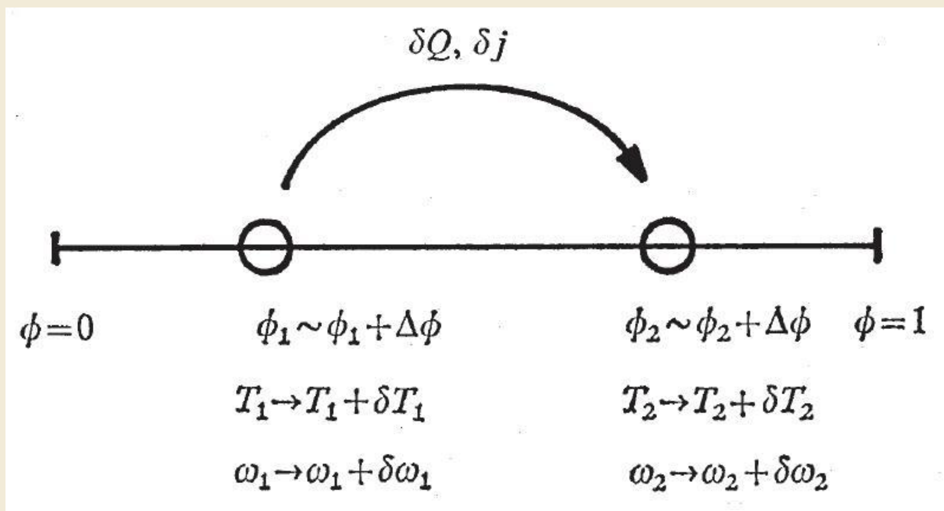
Gravothermal system with rotation

Parallelism

intensive variable	T	ω
extensive variable	s	j

W: Liapunov fn

$$\delta^2 W = -\int_V (\delta T \delta s + \delta \omega_z \delta j_z) d\boldsymbol{a} < 0 \ ,$$



Initial equilibrium state holds by balance among grav force, pressure grad, & centrifugal force

initially:

T=const ↓ ω=const

gradient appears spontaneously :

further proceeds

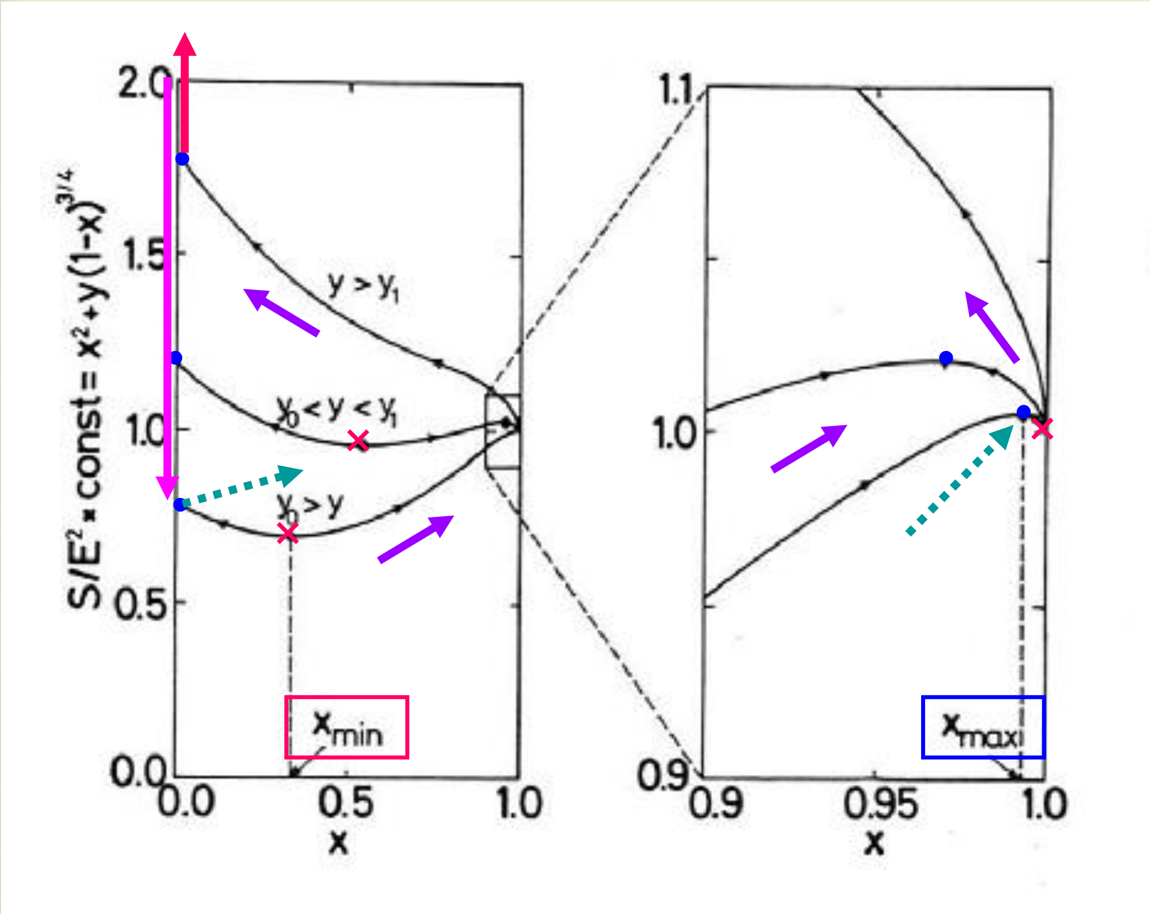
s-flow ↓ j-flow

the gradient grows unstably

similar to artificial earth satellite
losing its kinetic energy in atmosphere
losing its j (transferring outwards)
→ its total energy increases, ω increases
gradient in ω increases

Cosmology

Sugimoto et al, Prog Theor Phys Suppl #70, 1981)



$$x = M_{BH}c^2/E\,,$$

$$E = M_{BH}c^2 + aT_r^4 V$$

$$S_{tot} = S_{BH} + S_r$$

$$y = [a(T_g/3\pi)^4 V/E]^{1/4}(m_g c^2/E)$$

BH + rad

- • (local) max
- × (local) min

within particle horizon

→ inflation (decrease in E)

→ early expansion (increase in E)

for comoving volume

⋯→ rapid phase transition (E=const; nucleus formed by gravotherm)

Our World
Nesting of non-equilibria

Non-eql universe due to expansion

- ⊃ Nuclides out of equilibrium, stars vs interstellar space driving stellar evolution
  - ⊃ The sun and the earth
    - ⊃ Different Temperatures between earth surf and top of atmosphere
      - ⊃ Atmosphere of unsaturated humidity
        - ⊃ Lives as non-equilibrium open system in steady state

Reference 1

- I.Hashisu,Y.Nakada,K.Nomoto & D.Sugimoto, 1978;Gravothermal Catastrophe of Finite Amplitude,PThPh,60,393
- D.Sugimoto,Eriguchi Y.,Hachisu I.,1981,Gravothermal Aspects in Evolution of Stars and the Universe,PThPh,70,154
- http://map.gsfc.nasa.gov/
- D. Lynden-Bell & R. Wood, 1968; The gravo-thermal catastrophe in isothermal spheres and the onset of red-giant structure for stellar systems,MNRAS,138,495