第一课：混沌科学——历史与故事

主讲人：陈关荣

香港城市大学

主要内容

- 1 从经典三体问题谈起
- 2 现代混沌科学的诞生
- 3 混沌工程技术的希望
- 4 离散混沌和文史故事
- 5 漫无边际的混沌宇宙

CHAOS

Acknowledgement:

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从中学物理开始吧 ...

单体问题

(1643-1727)

牛顿运动定律 (1686)

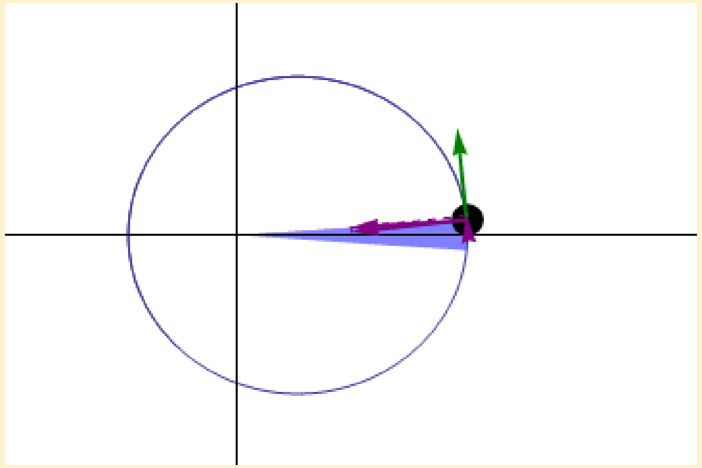
第一定律：
没有外力作用下的物体保持静止或匀速直线运动状态。

第二定律： $F = ma$
物体的加速度跟物体所受的外力的合力成正比，跟物体本身的质量成反比，加速度的方向跟合力的方向相同。

第三定律： $F_a = - F_b$
两个物体之间的作用力和反作用力大小相等方向相反并且作用在一条直线上。

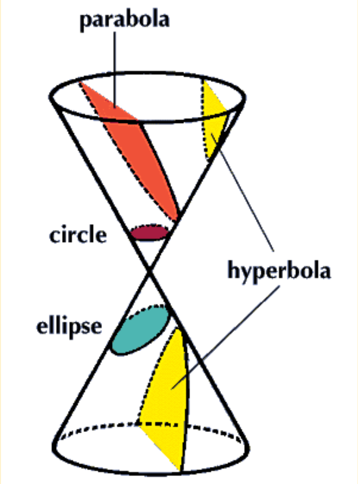
二体问题

二体问题又叫开普勒 (Kepler) 问题，在1710年由瑞士数学家伯努利 (Bernoulli) 首先解决：

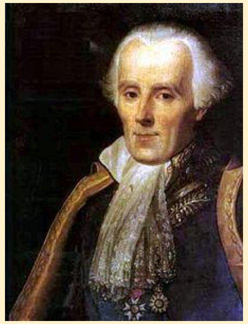


如果两个物体以连心力互相作用，则力的大小与它们距离的平方成反比。

如果你站在一个质点上看另一个质点，那么另一个质点的轨道一定是一条直线、或者一条抛物线、或者一个椭圆、或者双曲线的一支。



拉普拉斯 Laplace‘s Demon 魔咒



(1749-1827)

“我们可以认为宇宙的现在是由它的过去来决定的；现在也是决定未来的原因。如果有一位智者在某一时刻获知了自然界一切物体的位置和相互作用力，并且他具有超常的数据分析能力，那么他就可以把宇宙这个最庞大的物体直至到原子这个最细微的颗粒全都囊括到一个公式中去。对于这位智者来说，没有什么东西是不确定的——宇宙的未来会像它的过去一样完全呈现在他的眼前。”

-- Marquis Pierre Simon de Laplace (1814)

三体问题

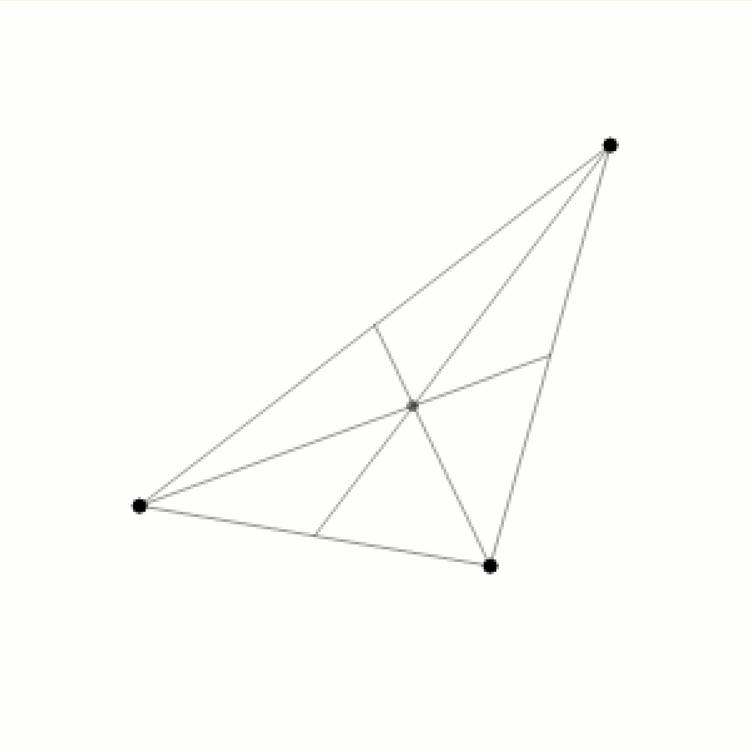
三体问题是天体力学中的基本力学模型，研究三个可视为质点的天体在相互引力作用下的运动规律。这三个天体的质量、初始位置和初始速度都是任意的。

例如：太阳、月亮和地球

在一般三体问题中，每一个天体在其他两个天体的万有引力作用下的运动方程都可以表示成 3 个二阶的常微分方程，或者 6 个一阶的常微分方程。因此，一般三体问题的运动方程为十八阶，必须求得 18 个完全积分才能得到完整的解析解。然而，目前还只能得到 10 个这样的积分，远未能解决三体问题。

N 体问题的第一个完整数学描述出现在牛顿的“自然哲学之数学原理”之中 (Philosophiae Naturalis Prinicipia Mathematica, 1687)

三体问题



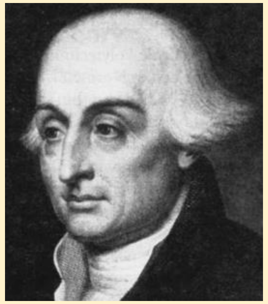
牛顿没能解决它。。。

欧拉、拉格朗日、拉普拉斯、泊松。。。也未能解决它

N体问题

限制性三体问题

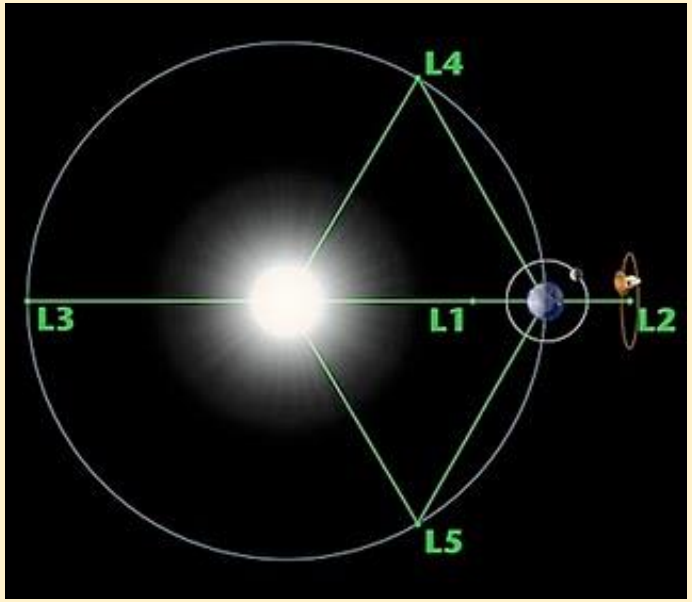
简化为“平面限制性三体问题”:
假定两个大质点作平面圆周运动，
一个小质点作空间运动。



(1736-1813)

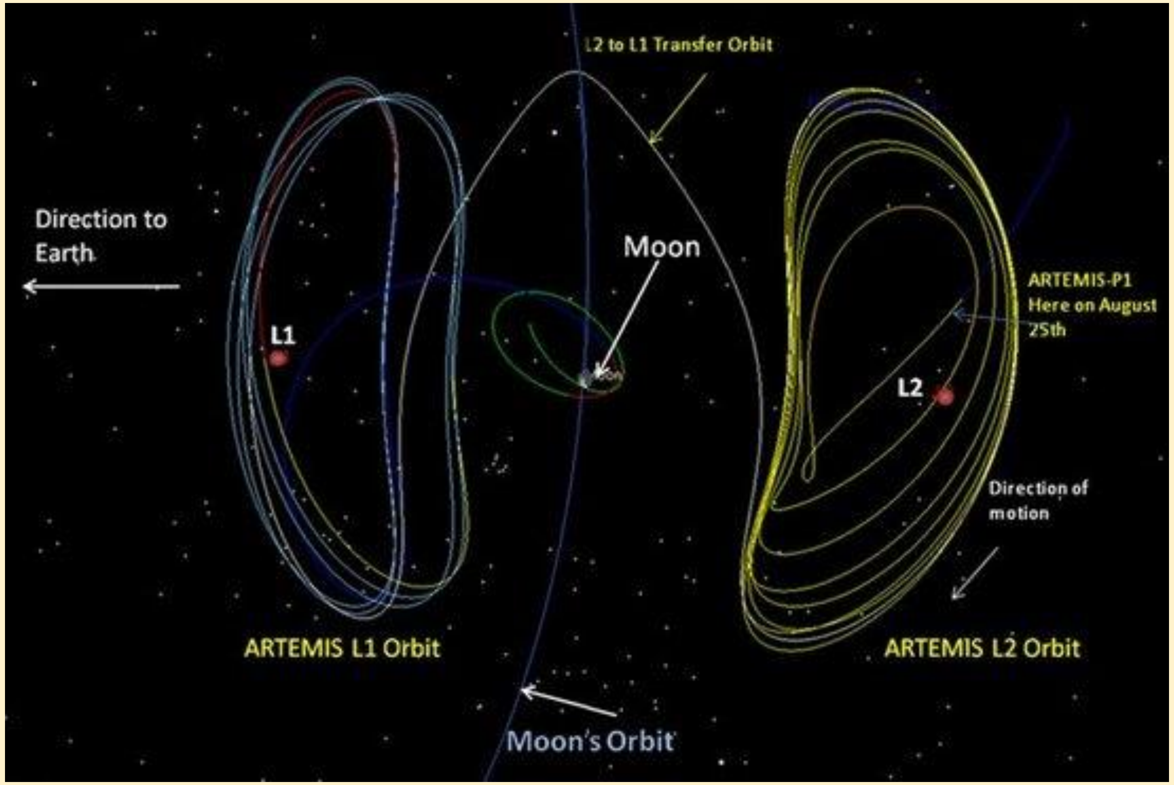
1772年，拉格朗日在这种限制条件下找到了 5 个特解，即著名的“拉格朗日点” 。

图示：木星和太阳连线上有 L1，L2，L3 三个拉格朗日点，而在木星轨道上则有 L4，L5 两个点，和太阳以及木星构成等边三角形。L1，L2，L3 是不稳定的； L4，L5 则是稳定的。



木星 - 太阳 - 地球

三体问题一个具体例子:



探测器进入月球轨道 示意图

1990s，美国宇航局经过半年时间和90多次超大型仿真详细地论证了：如果合理地利用地球至月球之间的正确转移轨道的话，将探测器从 L1 轨道转移到 L2 轨道所需要的燃料将比当前使用的大为减少。

2011年6月22日，美国宇航中心 月亮与狩猎女神" ARTEMIS 计划的第一个探测器成功进入月球轨道。它进行了一次空间飞跃：从 L1 轨道转移到 L2 轨道。

Aviation: Exploiting Unstable Periodic Orbits of a Chaotic Invariant Set for Spacecraft Control

NASA 科学家们成功地用很少量残余氢燃料把飞船 ISEE-3/IEC

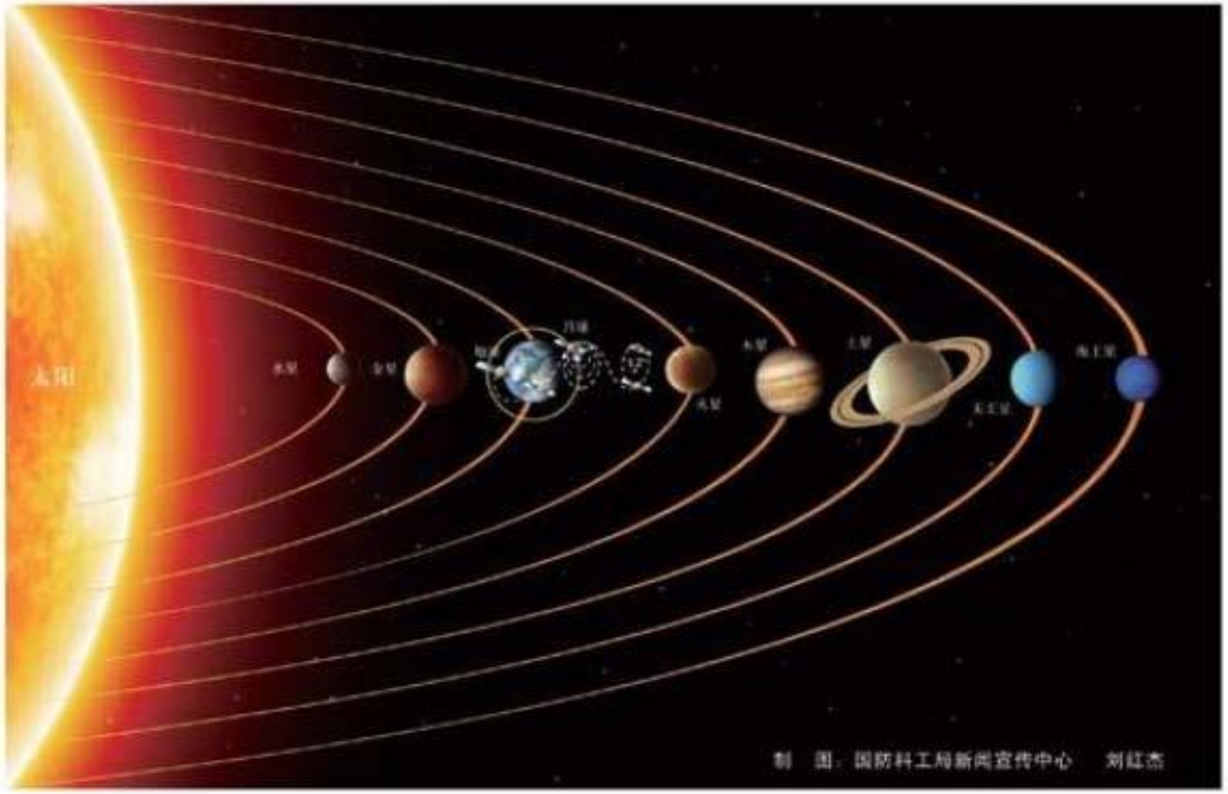
在太阳系空间里送到 5 千万英里之外的地方

The sensitivity of chaotic systems to small perturbations can be used to direct system trajectories to a desired target quickly with very low (or minimum) control energy. As an example, NASA scientists used small amounts of residual hydrazine fuel to send the spacecraft ISEE-3/IEC more than 50 million miles across the solar system, achieving the first scientific cometary encounter. This control action utilized the sensitivity to small perturbations of the three-body problem of celestial mechanics, which would not be possible in a nonchaotic system since it normally requires a huge control effort

Celestial Mechanics and Dynamical Astronomy, 87(3): 291-305 (2003)

中国的嫦娥

嫦娥二号卫星飞往日地拉格朗日L2点示意图



2011 年

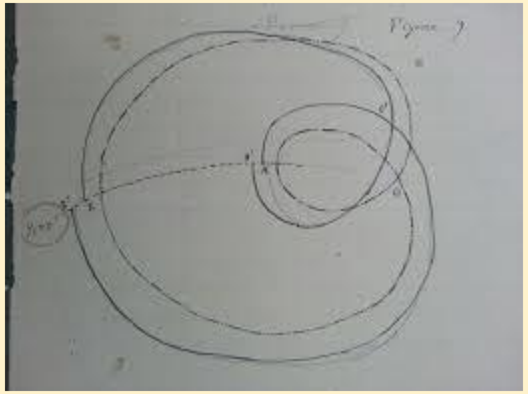
记者从国家国防科技工业局得到消息，截至8月30日，我国第二颗月球探测卫星嫦娥二号已环绕拉格朗日L2点稳定运行近5天时间，预计9月1日与太阳、地球、L2点处在同一平面内。这标志着嫦娥二号成功完成了各项拓展试验，我国在航天领域取得又一重要跨越，为我国探月工程后续任务及深空探测的开展奠定了坚实的基础。

三体问题

(1854-1912)

庞加莱 Henri Poincaré

1887年瑞典国王奥斯卡二世 (Oskar, II) 悬赏，征求太阳系稳定性问题的解答，期望解决天体力学中的 N 体问题。



庞加莱获奖论文手稿

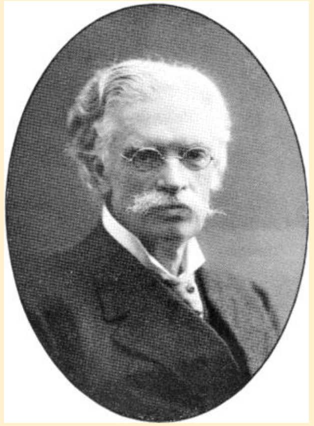
庞加莱以他关于三体问题的研究成果获得大奖。

国王和他的评审团

King Oscar II

K. Weierstrass

C. Hermite



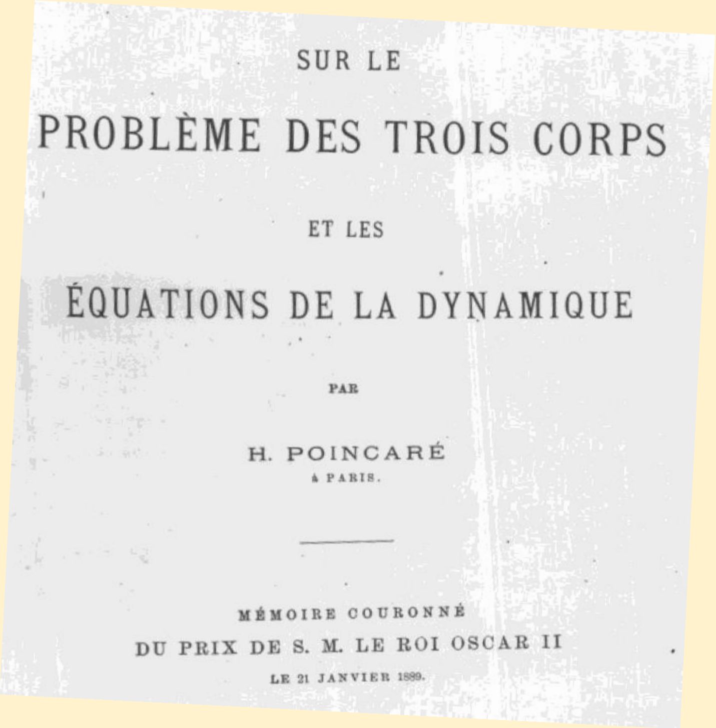
G. Mittag-Leffler

三体问题

庞加莱的原文内容被发现有错。。。
一直到1890年修订版才问世。

L. E. Phragmen:
Acta’s copy editor,
proof reader

这个重要的错误，后来变成了好事，导致他深思熟虑之后彻底地改变了传统的定量分析方法，以定性分析重新探讨了这个数学上极其艰深的问题，并开启了二十世纪动力系统定性理论、特别是混沌理论的先河。



SUR LE

PROBLÈME DES TROIS CORPS

ET LES

ÉQUATIONS DE LA DYNAMIQUE

PAR

H. POINCARÉ
À PARIS.

MÉMOIRE COURONNÉ
DU PRIX DE S. M. LE ROI OSCAR II
LE 21 JANVIER 1889.

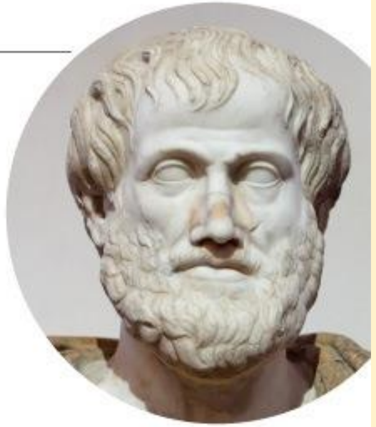
Acta Mathematica
13, 1-270, 1890.

混沌幽灵的浮现

A Brief History of Chaos

350BC

In *On the Heavens*, **Aristotle** writes, “The least initial deviation from the truth is multiplied later a thousandfold,” showing that the ancients understood that small changes can lead to big effects.



亚里士多德（前384-322）：

“对真实性极小的初始偏离，往后会被成千倍地放大”。

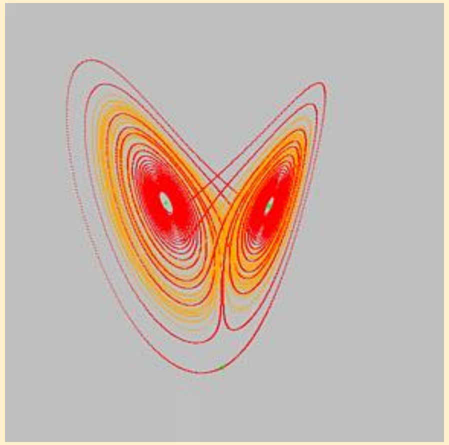
混沌幽灵的浮现

- 麦克斯韦尔 (Maxwell) 在 1873 年说过，系统初始状态的一个无穷小变化可能会引起状态在有限时间内出现有限的偏差，这样的系统称为是不稳定的。。。并且会使得对将来事件的预测成为不可能。
- 阿达马 (Hadamard) 在 1898 年也说过，初始条件中的误差或者不精确可能会使系统长时间的动力行为变得不可预测。
- 庞加莱 (Poincaré) 1908 年在《科学与方法》一书中写道："初始条件的微小误差在最后结果中产生极大差别的情况可能发生。。。于是预测变为不可能，从而我们就看到了许多偶然现象"。

参考 J. Gleick, Chaos: Making a New Science. 1987. 中译本《混沌学传奇》

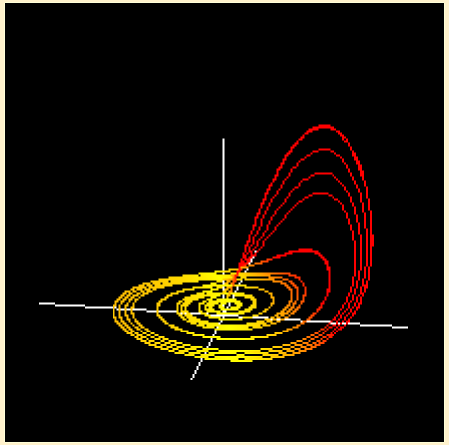
现代混沌科学的诞生

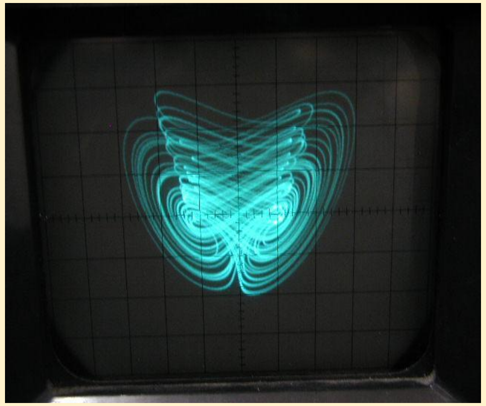
CHAOS

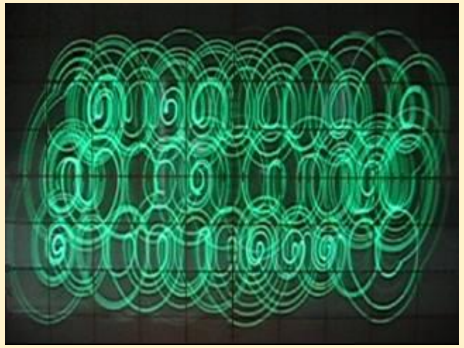


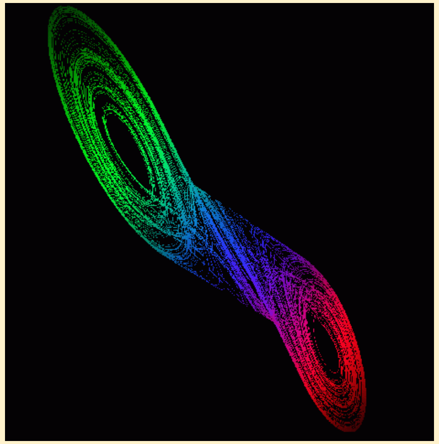
Edward Norton Lorenz

(1917-2008)









CHAOS

洛伦茨 – 美国 麻省理工学院 气象学教授

Lorenz 于 1991 年荣获 Kyoto Prize for "his boldest scientific achievement in discovering 'deterministic chaos,' a principle which has profoundly influenced a wide range of basic sciences and brought about one of the most dramatic changes in mankind's view of nature since Sir Isaac Newton."

Lorenz received the **Kyoto Prize** in **1991**

(A diploma, a 20K gold Kyoto Prize medal, and 50 million yen prize money)

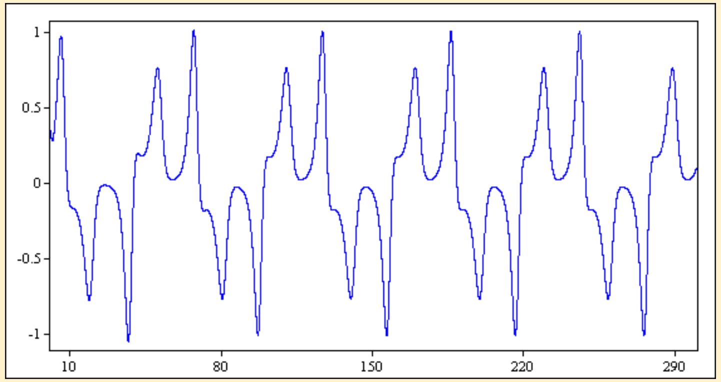
混沌天气模型

洛伦茨奉献毕生去研究 “长期天气预报”
以前被认为是一项需要耗尽人的一生精力、但却是 “less than science” 的研究

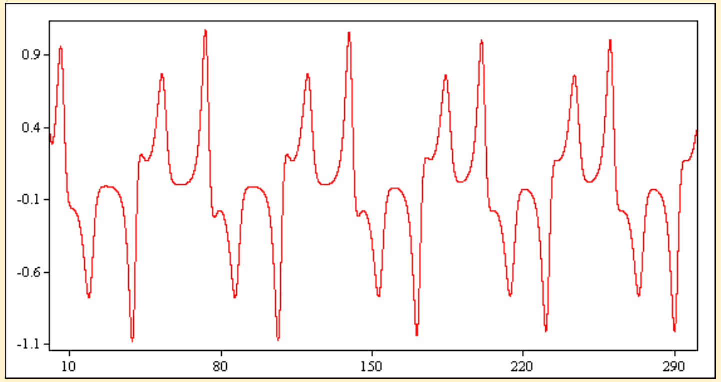
1961 年底某一天，洛伦茨在办公室里把一个数据输入到一台极其缓慢的 Royal McBee LGP-30 计算机，企图重复验证上一次的计算结果。

他知道这需要等一个多小时，便踱进了学院旁边的一间小小咖啡馆 。。。

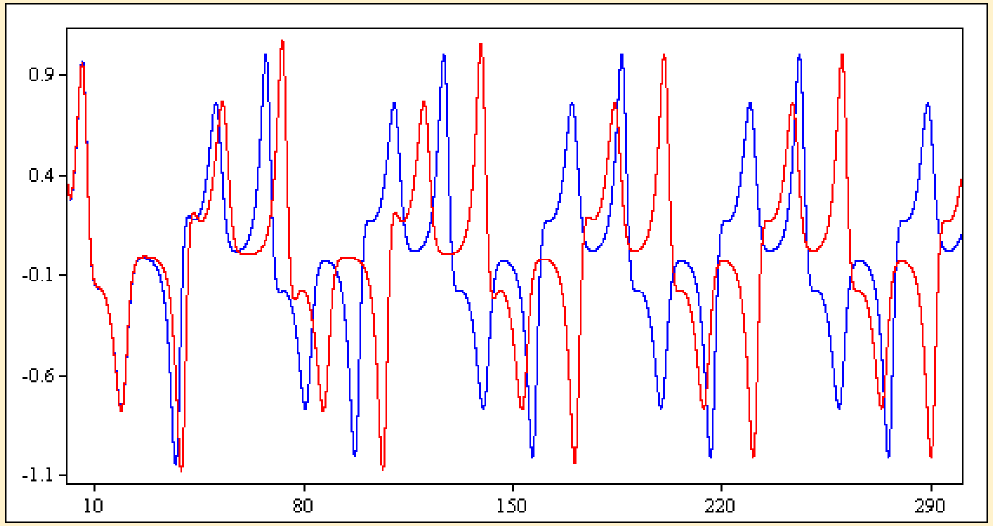
洛伦茨感到非常困惑 ...



yesterday



today



示意图曲线取自
Logistic map

洛伦茨的意外发现

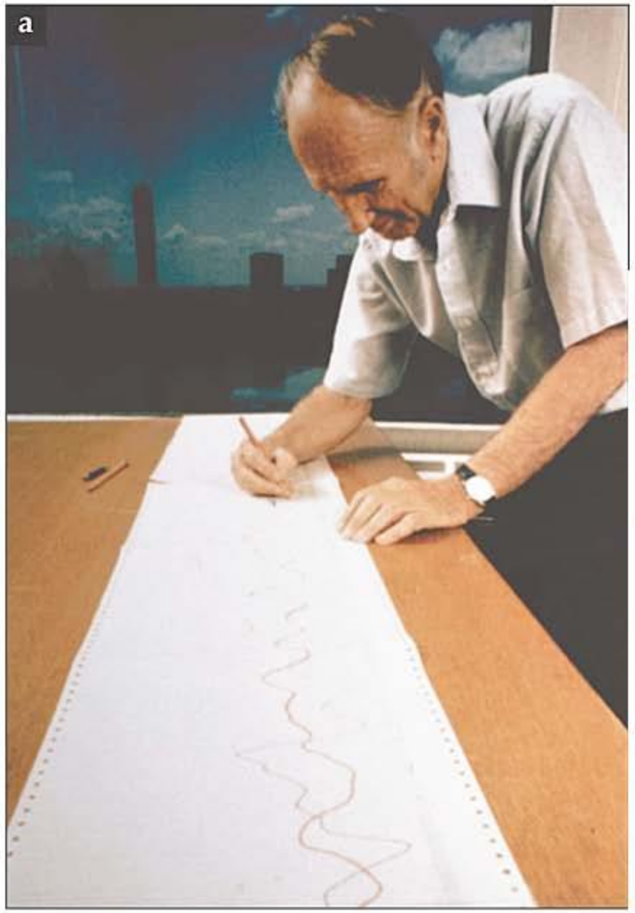
排除了计算机故障的可能性之后，他终于找到了缘由：

- 在第一次计算中，他输入的初始值是 0.506127
- 在第二次计算中，他图省事，输入了 0.506

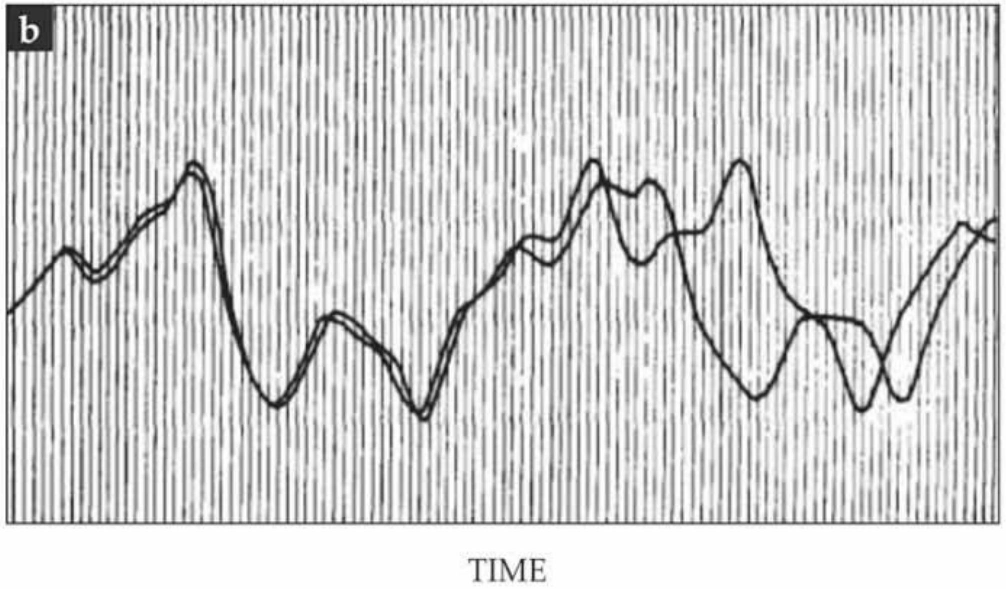
按理两者相差甚微 (千分之一)，当时科学计算中大家都采用“四舍五入”，结果应该只有微小差别不是吗?

他最后明白了 – 问题就出在这里 –
由于“系统对初值的高度敏感”， 一个微小的初始误差随着反复迭代计算酿成了巨大差异的后果。

洛伦茨的意外发现



这个意外让他发现了可以用简单明确的微分方程组写下来的“**混沌系统**”



Lorenz System

$$\begin{cases} \dot{x} = a(y - x) \\ \dot{y} = cx - xz - y \\ \dot{z} = xy - bz, \end{cases}$$

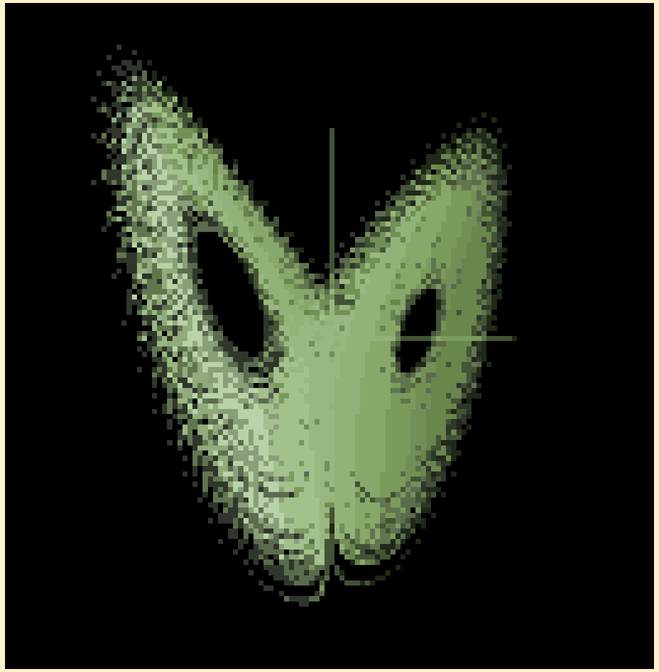
$$a = 10, b = 8/3, c = 28$$

不发散

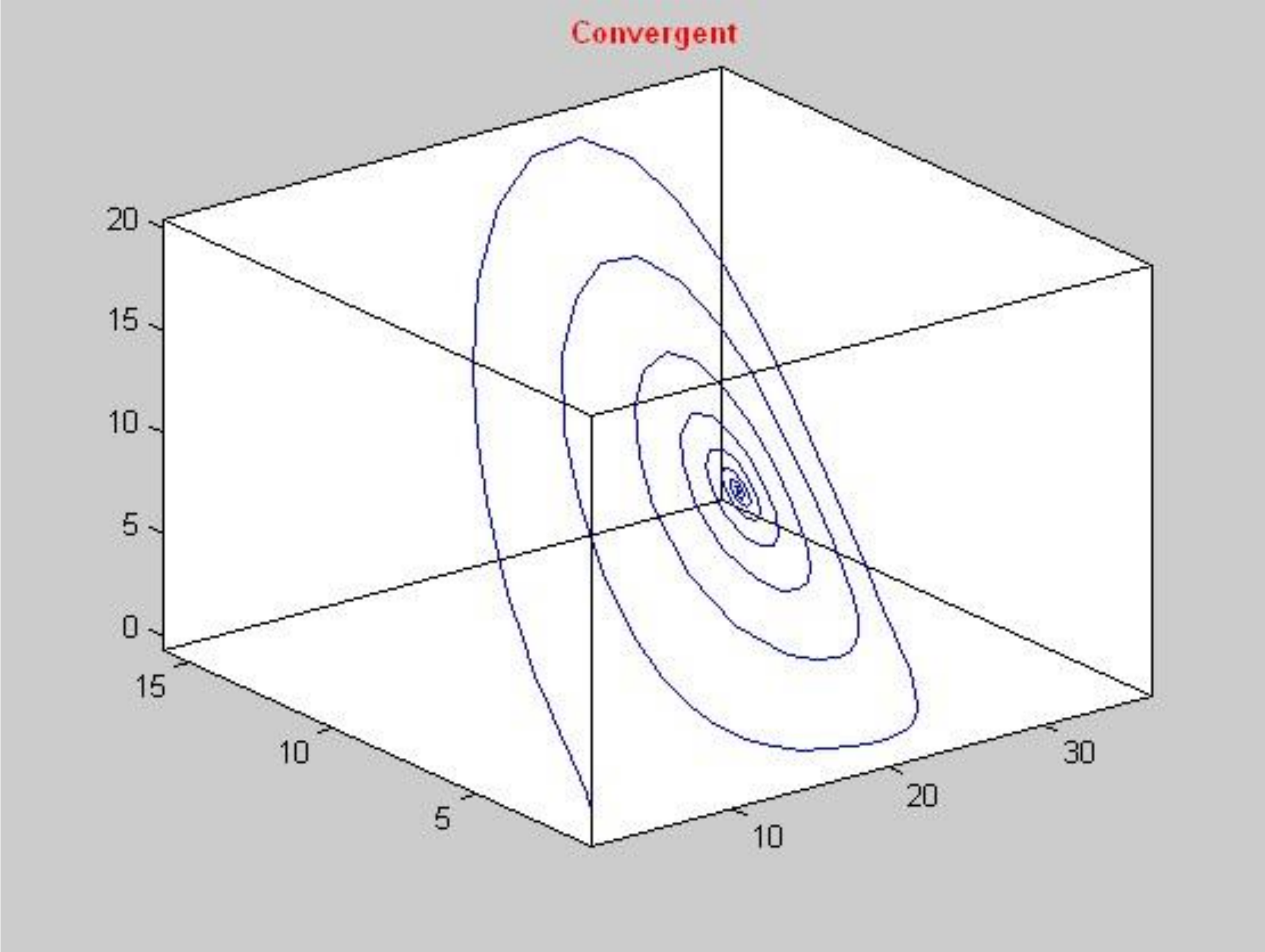
不收敛

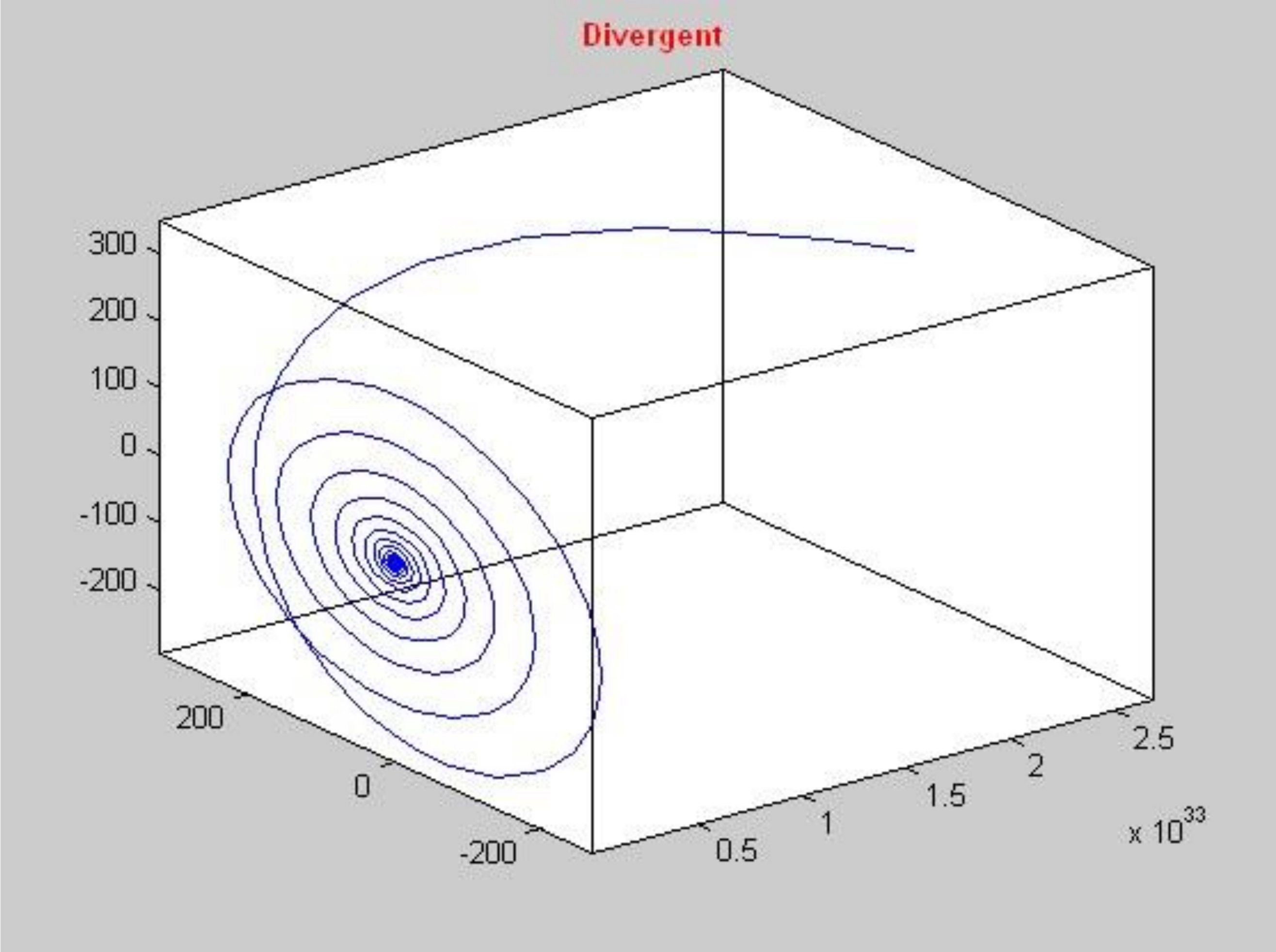
非周期

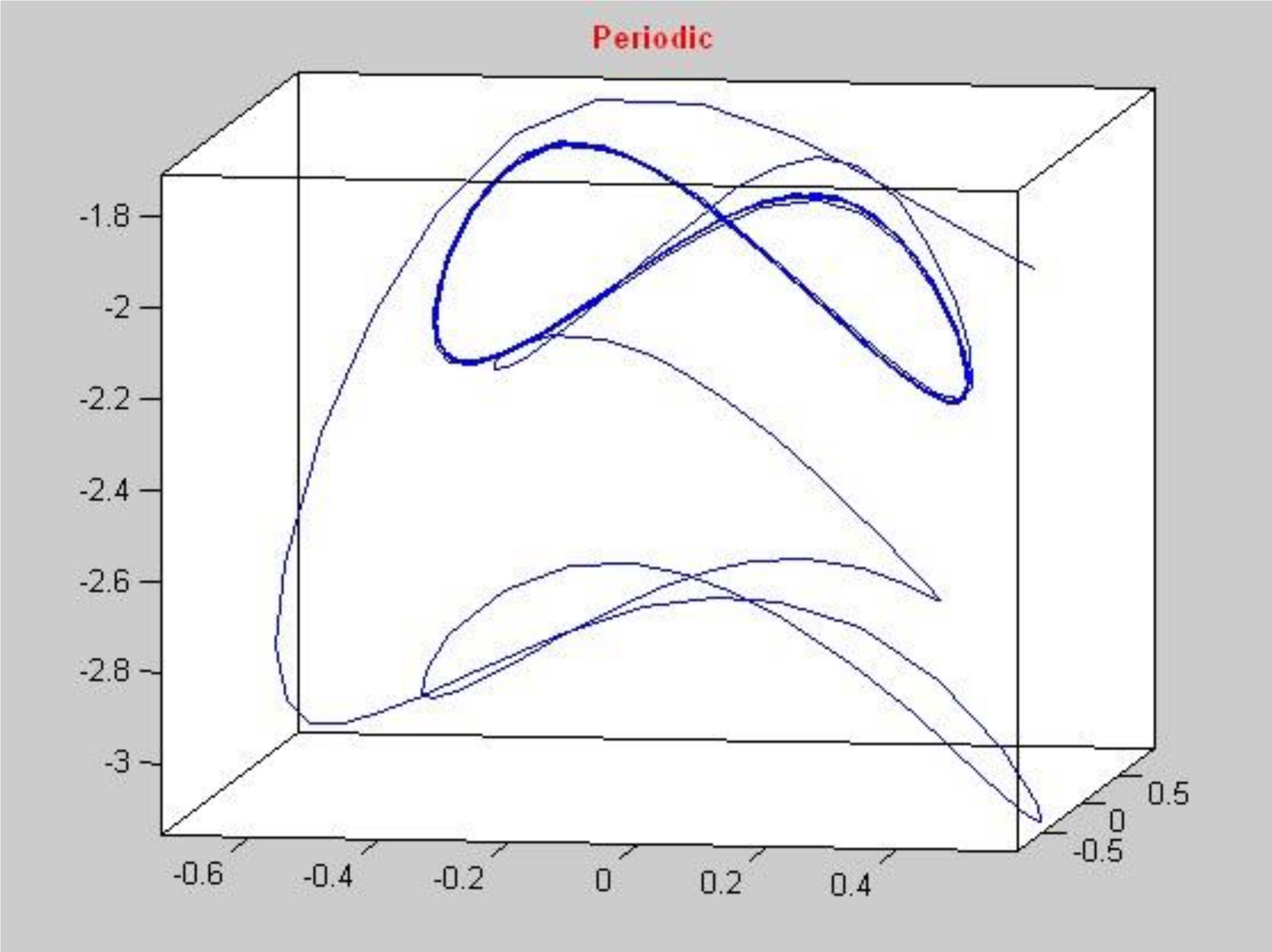
第2课（王雄）

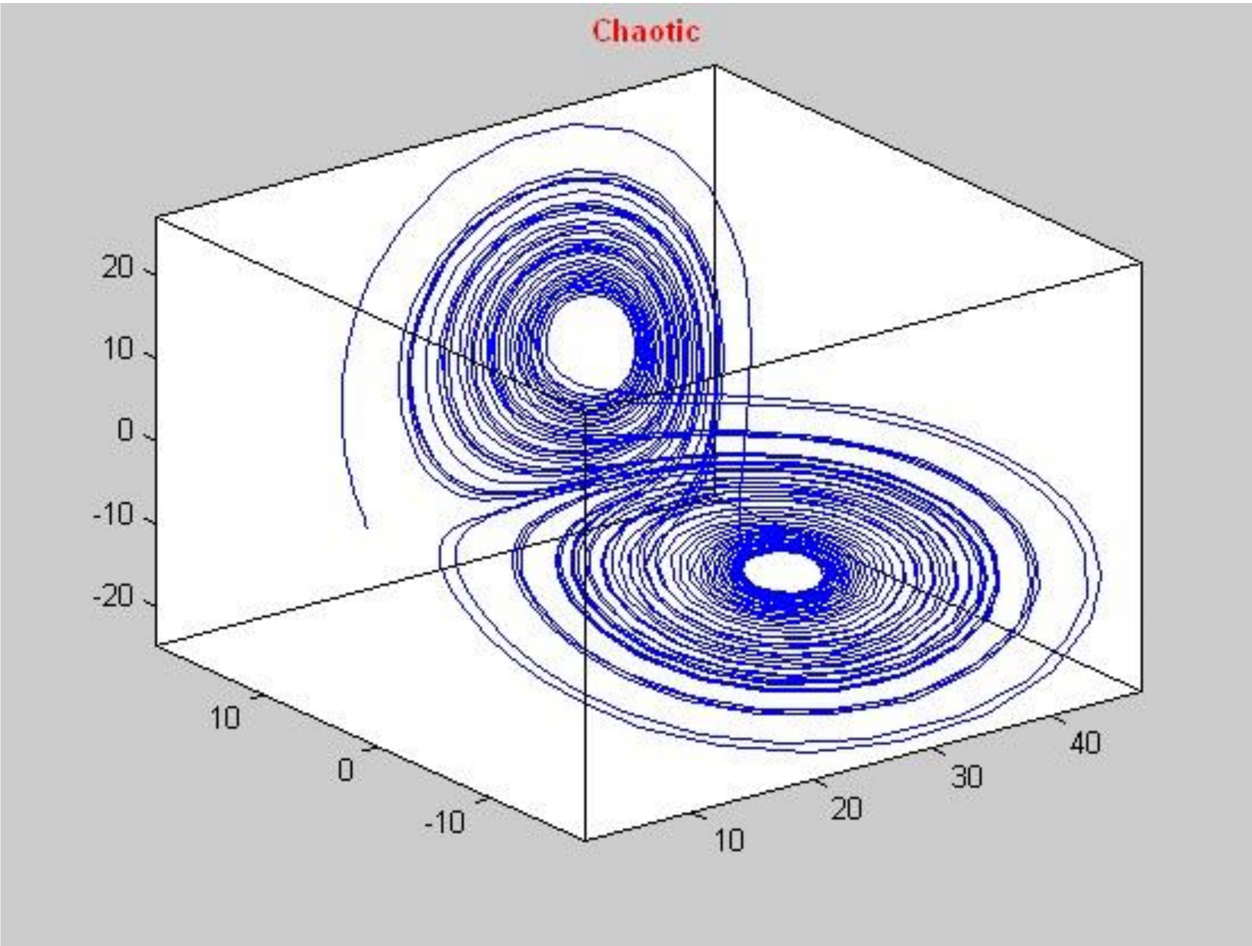


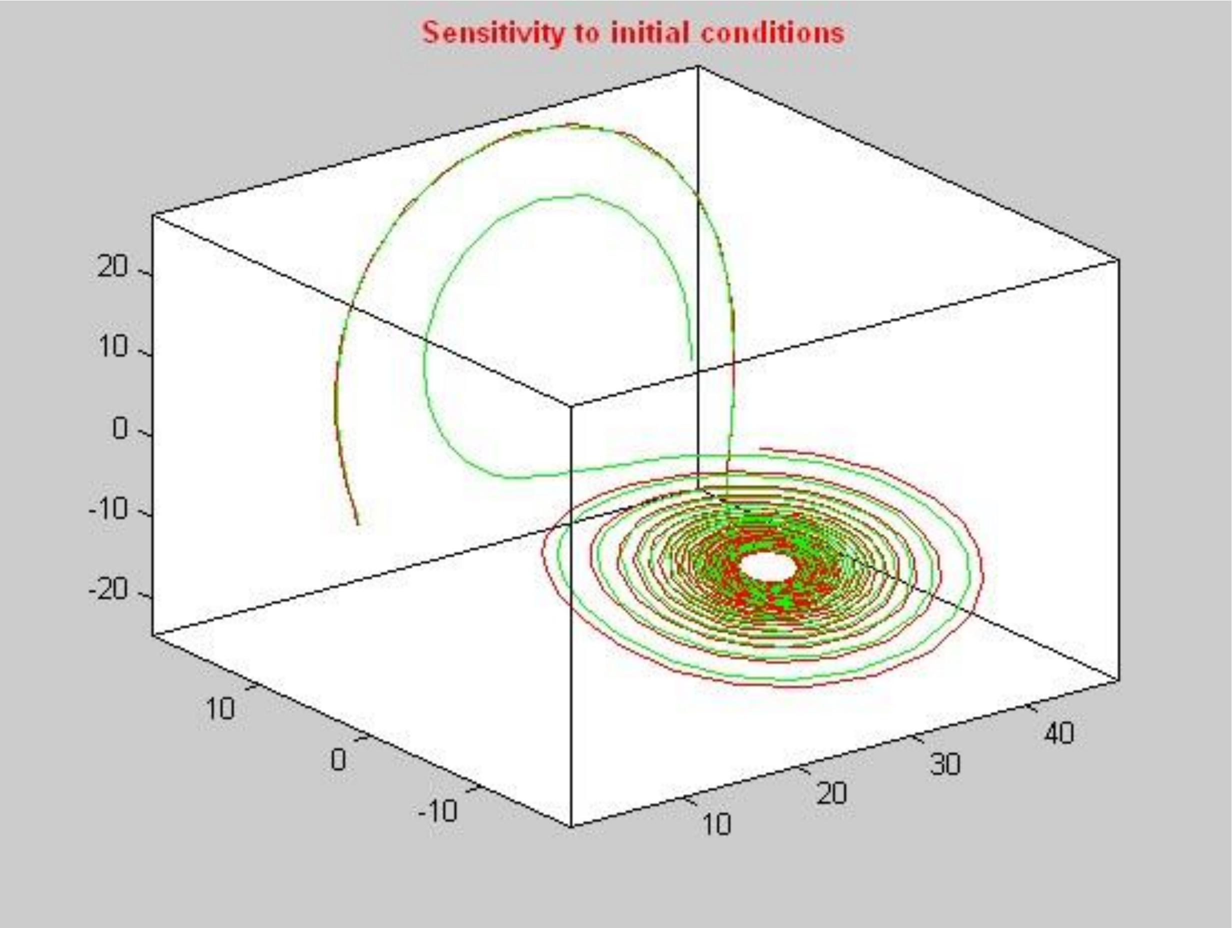
吸引子 “Attractor”


Convergent
20
15
10
5
0
15
10
5
10
20
30


Divergent
300
200
100
0
-100
-200
200
0
-200
0.5
1
1.5
2
2.5
x 10^33


Periodic
-1.8
-2
-2.2
-2.4
-2.6
-2.8
-3
-0.6
-0.4
-0.2
0
0.2
0.4
0.5
0
-0.5


Chaotic
20
10
0
-10
-20
10
0
-10
10
20
30
40


Sensitivity to initial conditions
20
10
0
-10
-20
10
0
-10
10
20
30
40

现代混沌科学的奠基性论文

洛伦茨把他的发现总结在下面一篇短文里：

E. N. Lorenz, "Deterministic nonperiodic flow,"
Journal of the Atmospheric Sciences, 20: 130-141, 1963

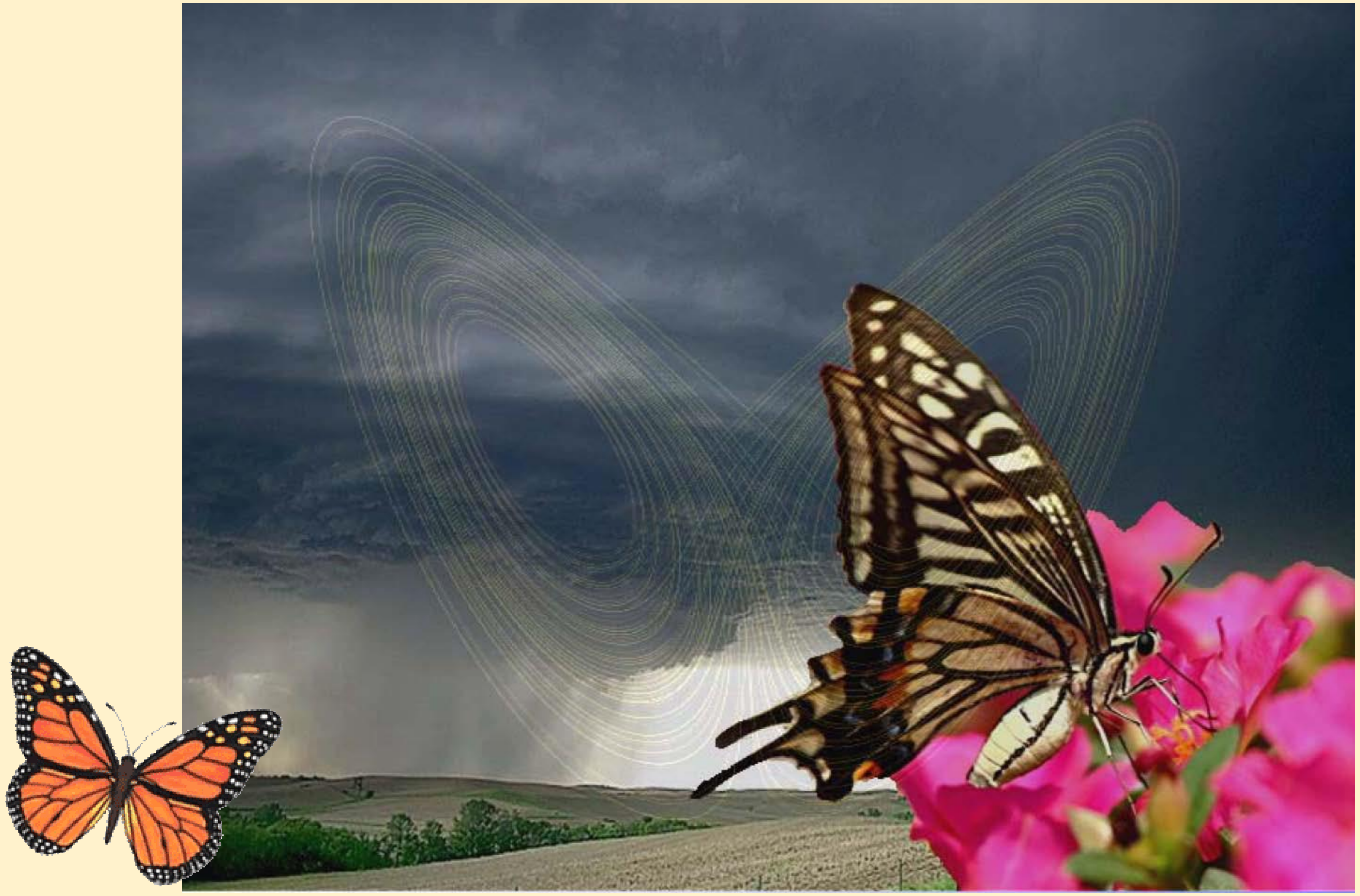
洛伦茨的结论：由于天气观测中存在着不明显的不精确性和不完全性，非常长期的准确天气预报是不可能的。

"洛伦茨这篇论文，在1960年代杂志上每年会被引用一次。可是二十年后的现在，它每年被引用的次数超过一百。"

- J. Gleick, Chaos: Making a New Science. 1987 中译本《混沌学传奇》

“Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?” – Edward N. Lorenz

“在巴西的一只蝴蝶拍打一下翅膀会在得克萨斯引发一场龙卷风吗？”



初始条件的重要性

有一首英文诗：

因为一根铁钉丢了，使得一个马蹄铁坏了。
因为一个马蹄铁坏了，使得一匹战马摔倒了。
因为一匹战马摔倒了，使得一个骑兵阵亡了。
因为一个骑兵阵亡了，使得一场战役输了。
因为一场战役输了，使得一个国家灭亡了。

初始条件的重要性

有一首英文诗：

因为一根铁钉丢了，使得一个马蹄铁坏了。
因为一个马蹄铁坏了，使得一匹战马摔倒了。
因为一匹战马摔倒了，使得一个骑兵阵亡了。
因为一个骑兵阵亡了，使得一场战役输了。
因为一场战役输了，使得一个国家灭亡了。

有一首中文诗 (苏轼)：

斫得龙光竹两竿，持归岭北万人看。
竹中一滴曹溪水，涨起西江十八滩。

成语

差之毫厘，
谬以千里。

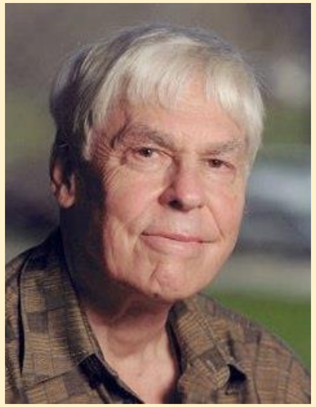
《易》曰：“君子慎始，
差若毫厘，谬以千里”。

—《礼记 · 经解》

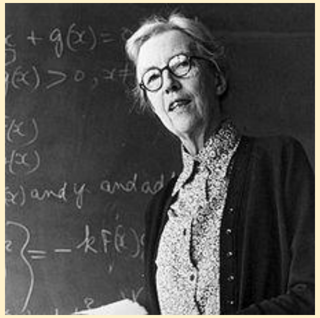
（约公元前210年）

严格混沌数学理论的诞生

- 1966年菲尔兹(Fields)奖 +
  2007年沃尔夫(Wolf)奖: 1/14
- 混沌理论中的“马蹄理论” —
- 斯梅尔1998年在文章 “混沌：在里约热内卢海滩上发现马蹄” 中回忆道: “…我原来的猜想错了。混沌已经隐含在 Cartwright 和 Littlewood 的分析之中！现在迷团已经解开，是我作出了错误的猜测。但是在这个学习的过程中，我发现了马蹄！ ”



Stephen Smale
(1930-)



Mary Lucy Cartwright (1900-1998)
John E. Littlewood (1885-1977)

斯梅尔和美国 NSF 的纠结　　原文摘抄

“In 1960 in Rio de Janeiro I was receiving support from the National Science Foundation (NSF) of the United States as a postdoctoral fellow, while doing research in an area of mathematics which was to become the theory of chaos. Subsequently questions were raised about my having used U.S. taxpayer's money for this research done on the beaches of Rio. ” [Critique came from the then NSF director D. Hornig]

“What happened during the passage of time from the work on the beaches to this national condemnation?”

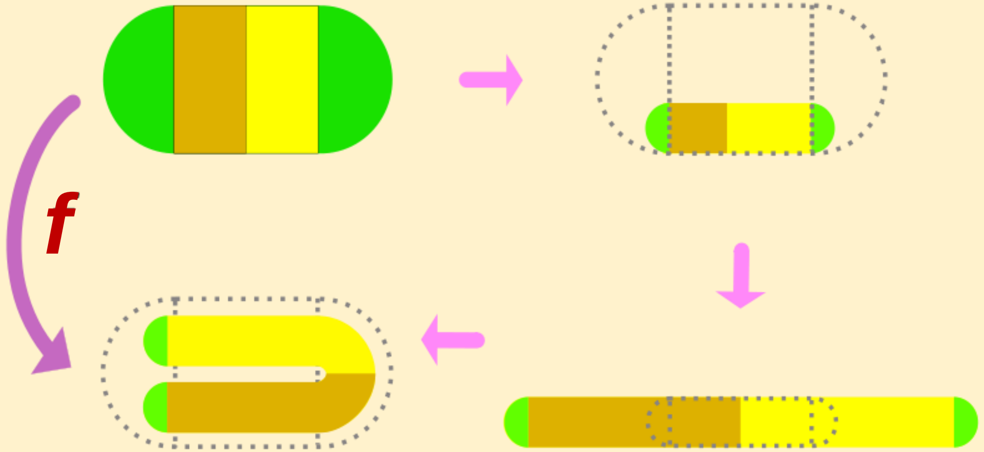
……

“Thus ‘... the mathematics created on the beaches of Rio ...’ (Hornig) was the horseshoe and the higher-dimensional Poincare's conjecture.”

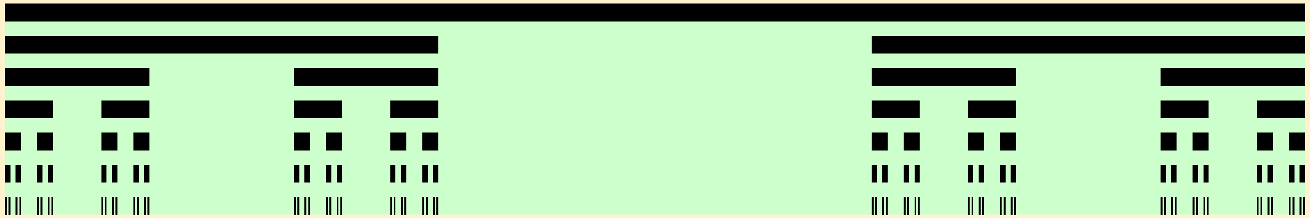
S. Smale: Finding a Horseshoe on the Beaches of Rio (1998)

马蹄映射

斯梅尔证明了: 无限次迭代马蹄映射的交集是一个康托集。
他进而证明了马蹄映射迭代过程的最终性态对初始条件的敏感依赖性 — 这正是混沌的本质



第4课（张旭）



Georg Cantor
(1845-1918)

后话

- 斯梅尔在1961年证明了维数大于 4 的 “广义庞加莱猜想”
- Michael Freedman 在1982年证明了 4 维的广义庞加莱猜想，从而获 1986 年菲尔兹奖
- Grigori Y. Parelman 在2002年证明了 “庞加莱猜想”，但拒绝了接受 2008 年的菲尔兹奖，也拒绝了 Clay 数学研究所一百万美元的奖金。

他认为 Richard Hamilton (1943-) 理应同时获奖

Michael Freedman

(1951-)

Grigori Parelman

(1966-)

发展史回顾：洛伦茨之前

早在1920年，范德波尔 (Balthasar van der Pol) **就提出了一个无线电波振动微分方程：**

$$\ddot{x} - k(1 - x^2)\dot{x} + x = bk\lambda\, cos(\lambda t + \alpha)$$

其中 k, b, λ, α 为参数。这方程与 瑞利勋爵（Lord Rayleigh, John William Strutt，1842-1919）的方程是等价的；它还可以看作是李纳德（Alfred-Marie Liénard，1869-1958）方程的一种特殊情形。

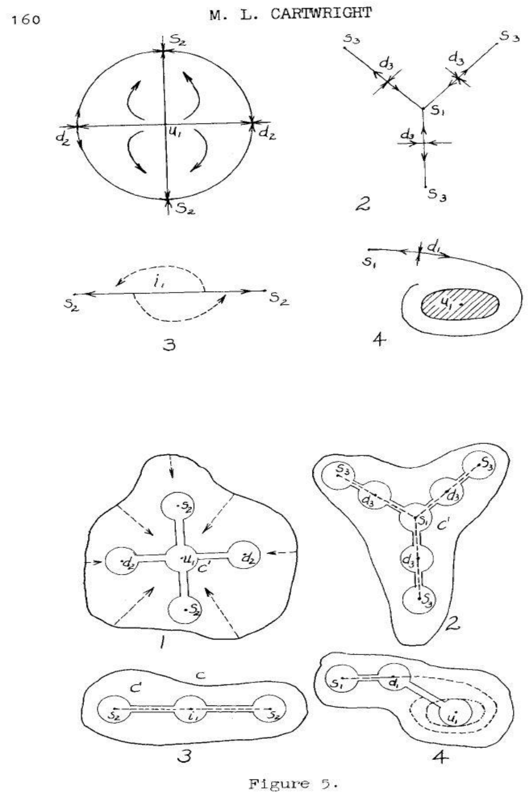
van der Pol
(1889-1959)

范德波尔于1927年9月在《Nature》杂志上发文报告了基于这个微分方程的霓虹灯实验，说当驱动信号具有某种自然频率时，会听到“毫无规律的噪声”。这篇文章很可能是观察到物理混沌现象最早的实验报告。

1940年代开始，受美国数学家乔治·伯克霍夫（George D. Birkhoff, 1884-1944）**和诺曼·莱文森**（Norman Levinson，1912-1975）**的影响，英国数学家玛丽·卡特赖特**（Mary Cartwright）**和约翰·李特尔伍德**（John Littlewood）**对 van der Pol 方程作了一系列深入的数学分析。。。**

她们注意到了方程初始条件和参数的不适当选取会导致方程解的不稳定性和不可预测行为，让对微分方程的分析和求解变得极其困难。

这其实就是“蝴蝶效应”。



玛丽的手稿

玛丽·卡特赖特的贡献

1960年代，玛丽研究周期驱动下一般二阶非自治非线性微分方程的“几乎周期解”（almost periodic solutions），并把其中一些结果推广到高维。

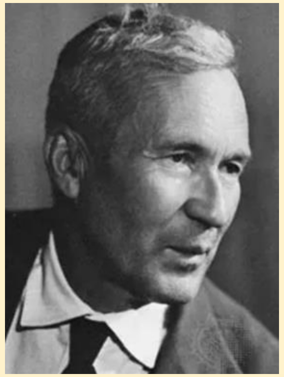
1964年，玛丽在《伦敦数学会会刊》上发表了著名论文：“从非线性振荡到拓扑动力学”。

至此，当说到“无穷多个不稳定的周期解”、“不可预测性”和“几乎周期解”，就离混沌的现代数学理论不远了。

苏联数学家的贡献

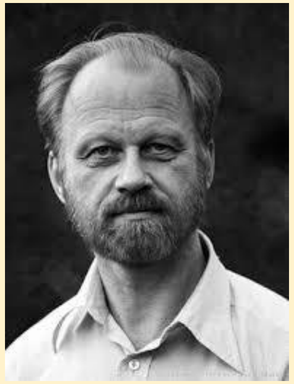
1954年世界数学家大会闭幕式报告里，苏联数学家安德烈·柯尔莫哥洛夫（Andrey N. Kolmogorov，1903–1987）不加证明地叙述了一个定理，试图解释浮点运算观察不到的混沌现象。后来，弗拉基米尔·阿诺德（Vladimir I. Arnold，1937-2010）和美国数学家尤尔根·莫泽尔（Jürgen K. Moser，1928–1999）补充了全部的细节，共同建立了著名的 **Kolmogorov-Arnold-Moser（KAM）**定理。

KAM 定理指出，微小扰动之下可积系统的环面只会变形而不会消失；但如果有环面受到破坏，它便会导致混沌。这一混沌产生过程类似于斯梅尔马蹄映射。后人还把**KAM**定理应用到太阳系统的稳定性分析。



Kolmogorov

Arnold

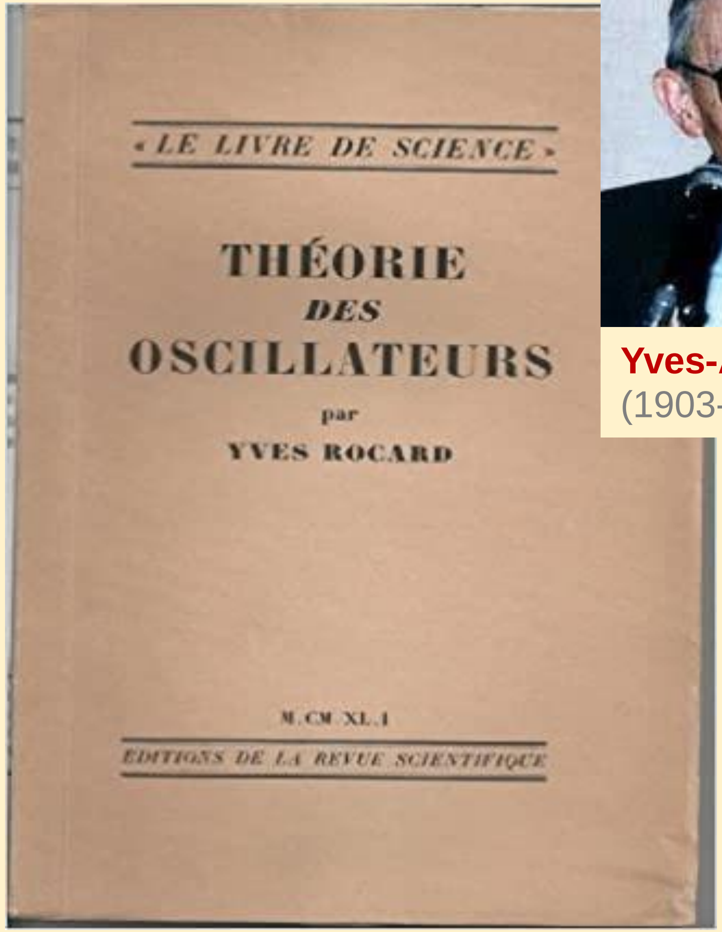


Moser

自庞加莱以来，数学家们似乎已经看到了混沌存在的幽灵，但始终没有人给出一个具体的微分方程例子 —— 直到洛伦茨

不过，混沌还有故事

1941年，法国物理学家伊夫–安德烈·罗卡德（Yves-André Rocard, 1903-1992）出版了一本法文著作《振荡器理论》（Théorie des oscillateurs）。



《振荡器理论》（1941）

Yves-André Rocard
(1903-1992)

罗卡德的书第五章题为“经济的振荡理论”（Les oscillateurs des thoreories economiques）。他基于 van der Pol 张弛振荡器方程设计了一个（当年他本人并不知道是混沌的）张弛经济振荡模型：

$$\begin{cases} \frac{dx}{dt} = -\omega(\varepsilon x + \omega y + \omega z) \\ \frac{dy}{dt} = \omega\left[\varepsilon + \eta\left(1 - z^2 - \frac{x^2}{\omega^2}\right)\right] z \\ \frac{dz}{dt} = x \end{cases}$$

这个混沌模型有两个三次项，而洛伦茨系统只有两个二次项。

无论如何，从时间来说，罗卡德的混沌系统比洛伦茨的发现早22年。

混沌很快就从物理数学来到工程技术

比洛伦茨略早的，还有日本京都大学的电子工程学教授上田睆亮（Yoshisuke Ueda，1936– ）。上田在**1961**年尚是研究生时就从实验室里观察记录了方程

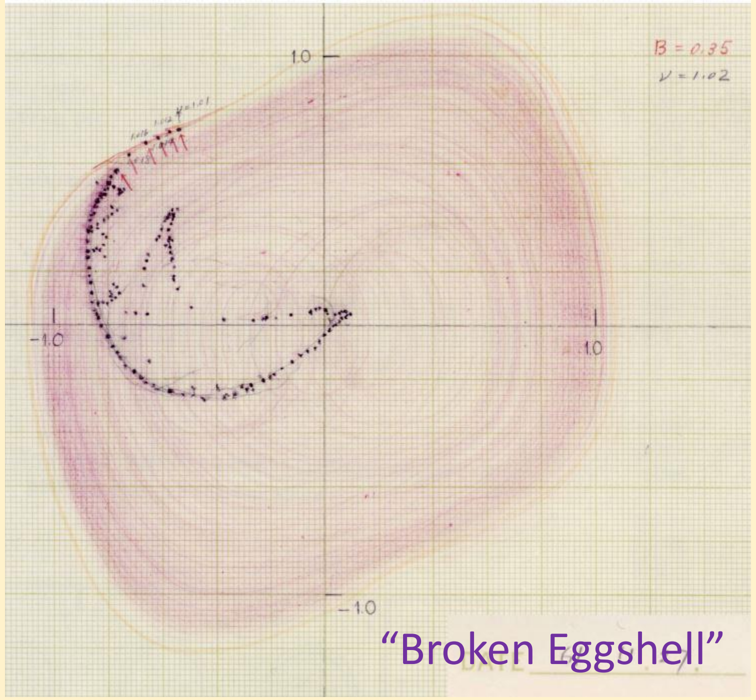
$$\ddot{x} - k(1 - hx^2)\dot{x} + x^3 = b\,cos(\alpha t)\ ,$$

$$k = 0.2, h = 8, b = 0.35, \alpha = 1.02$$

的混沌吸引子，称为日本吸引子（Japanese attractor）。

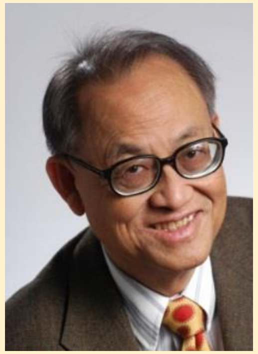
不过，后来他也知道，这个方程比杜芬（Georg Duffing，1861–1944）混沌方程还要复杂些。

上田睆亮

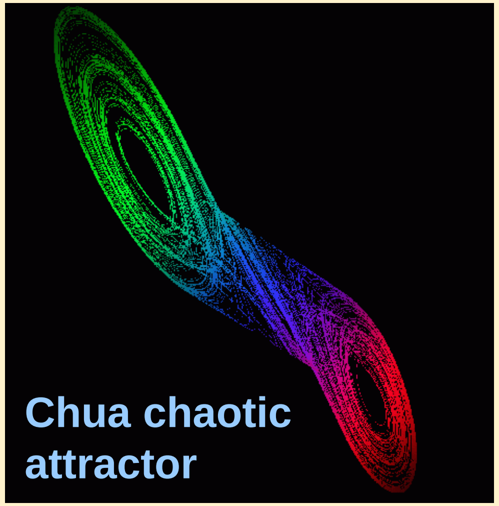


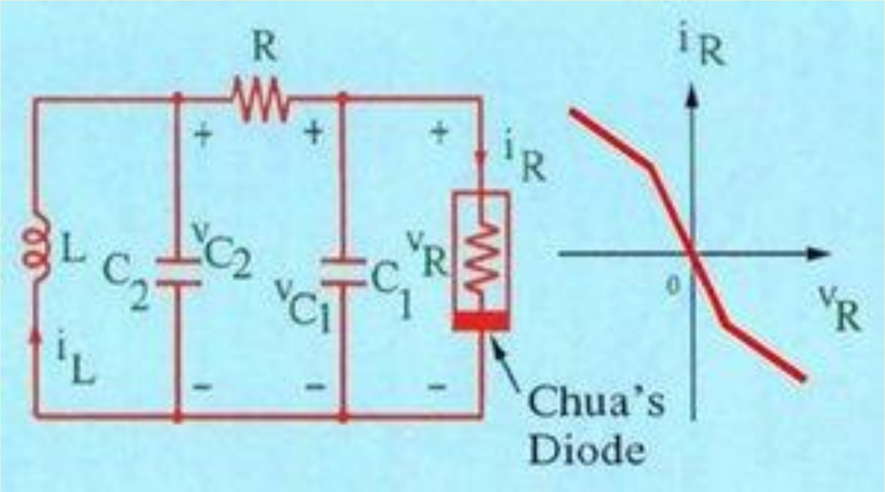
“Broken Eggshell”

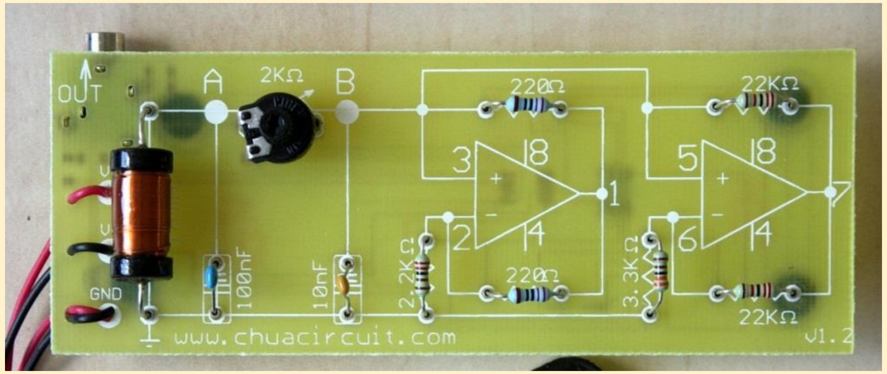
混沌电路



Leon O Chua 蔡少棠
(1936 -)







Chua 电路

第3课（李春彪）

第9课（禹思敏）

Chua's Circuit

Circuit equations:

$$\frac{dv_1}{dt} = \frac{1}{RC_1}(v_2 - v_1) - \frac{1}{C_1} f(v_1)$$

$$\frac{dv_2}{dt} = \frac{1}{RC_2}(v_1 - v_2) + \frac{1}{C_2} i_L$$

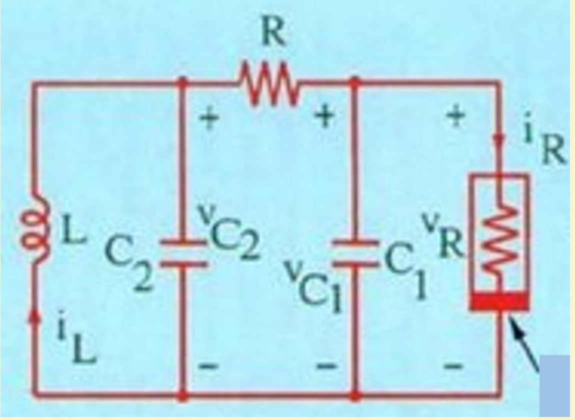
$$\frac{di_L}{dt} = -\frac{1}{L} v_2$$

Dimensionless Form:

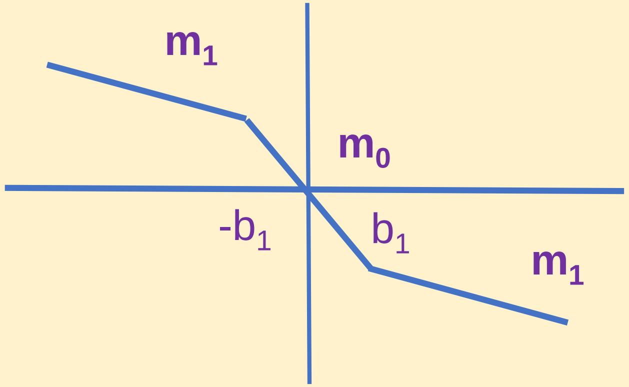
$$\dot{x} = \alpha (y - f(x))$$

$$\dot{y} = x - y + z$$

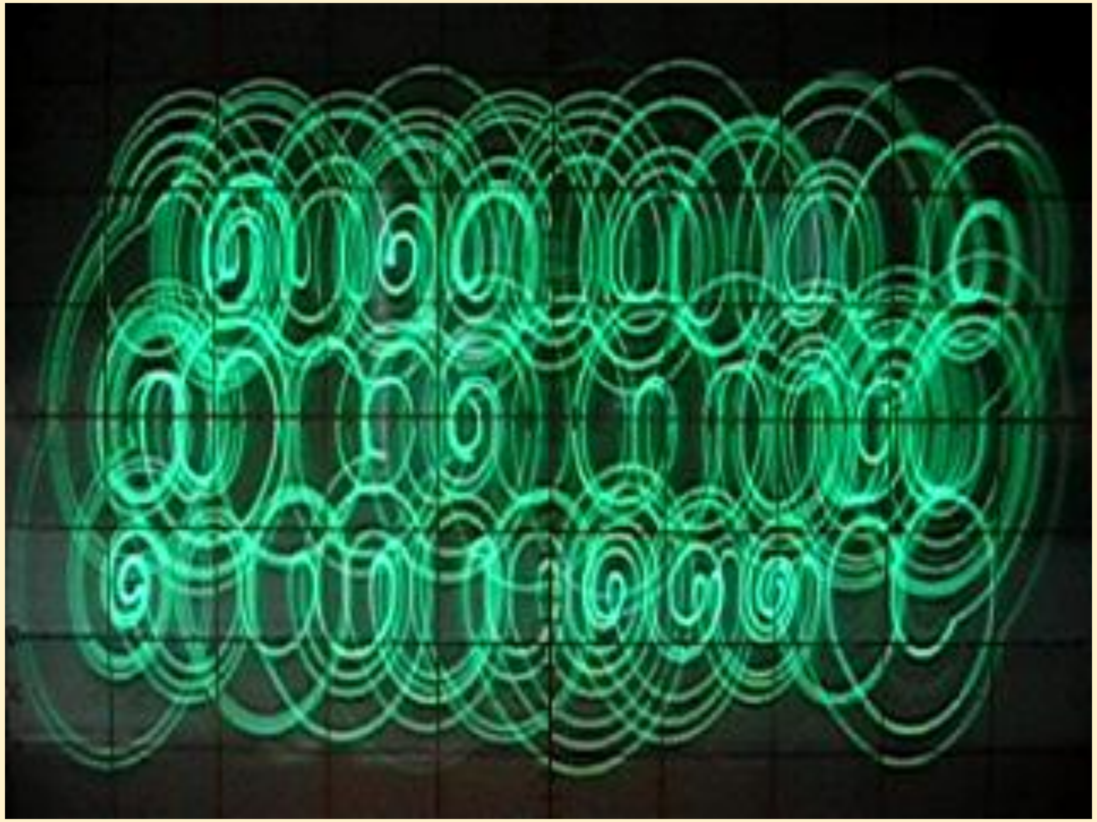
$$\dot{z} = -\beta y$$



$$f(v_1) = m_1 v_1 + \frac{1}{2}(m_0 - m_1)(|v_1 + b_1| - |v_1 - b_1|)$$

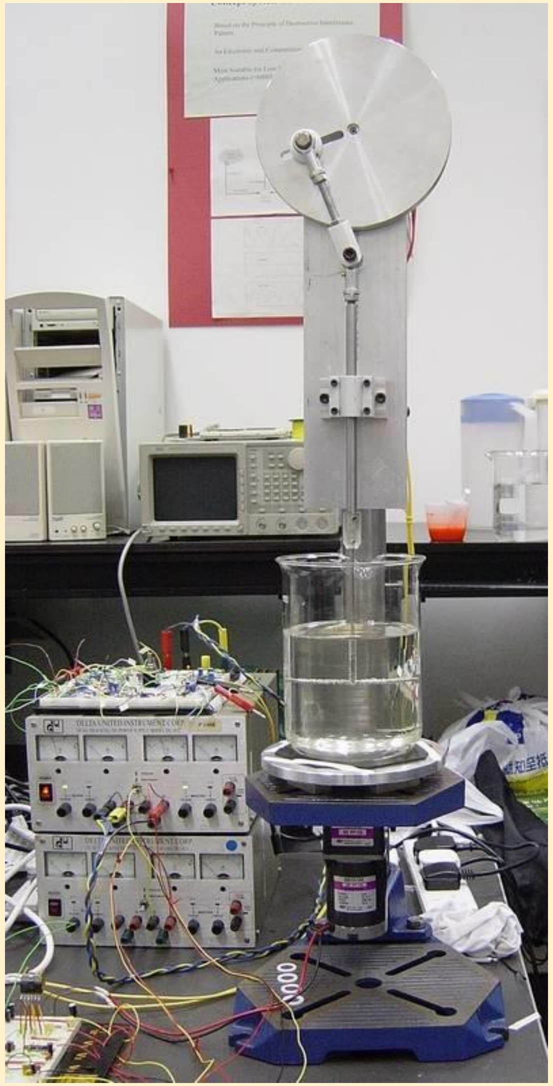


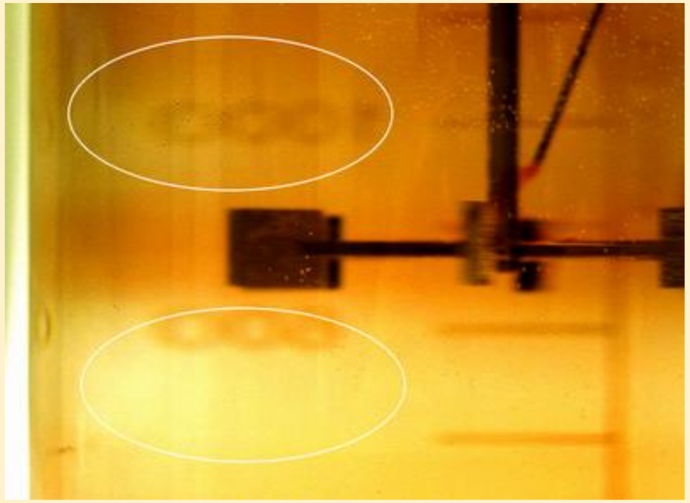
多涡卷混沌吸引子



混沌应用于液体搅拌：快速+均匀

Chua 电路 →

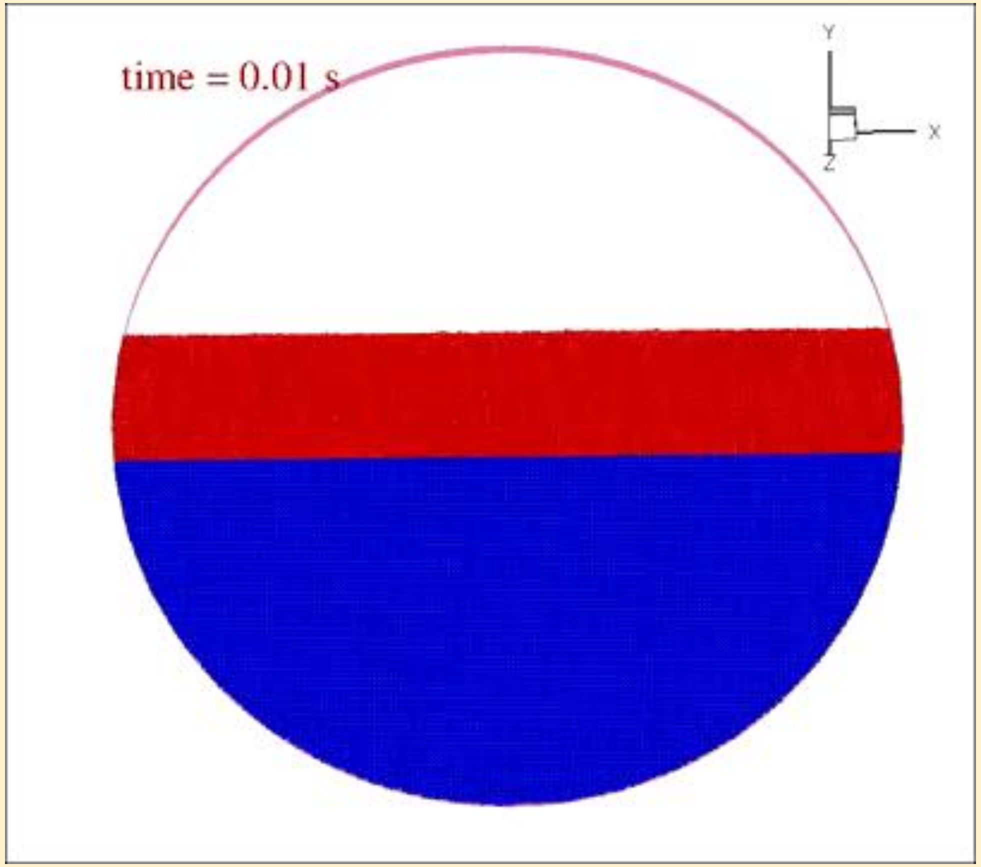


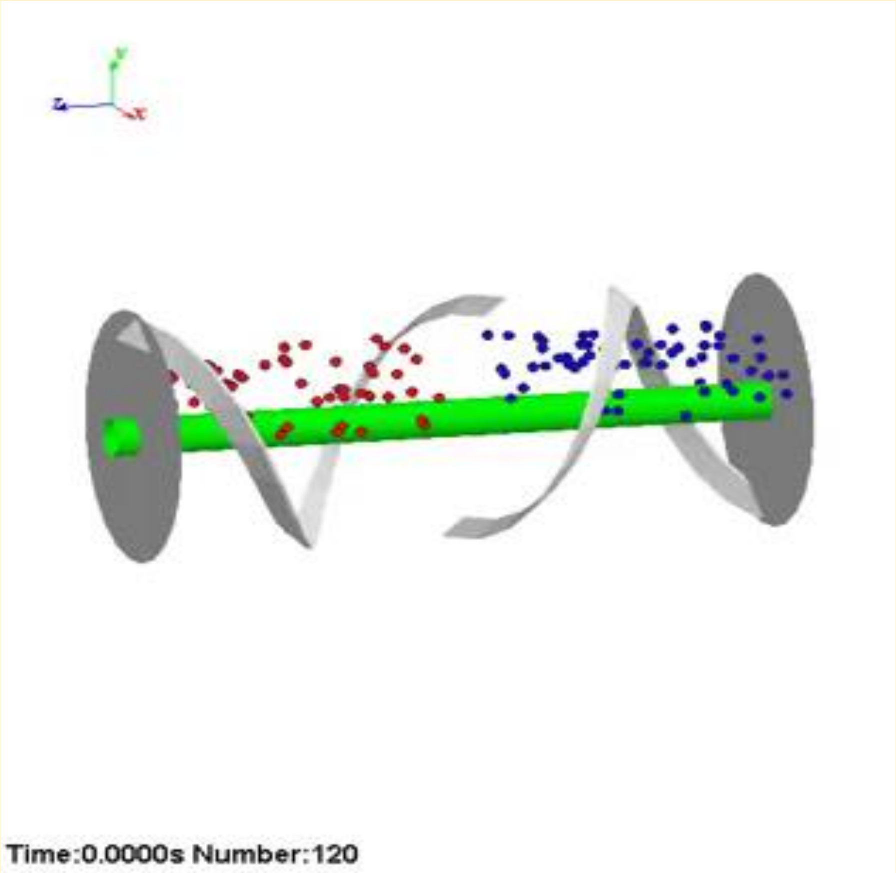


常规搅拌

混沌搅拌

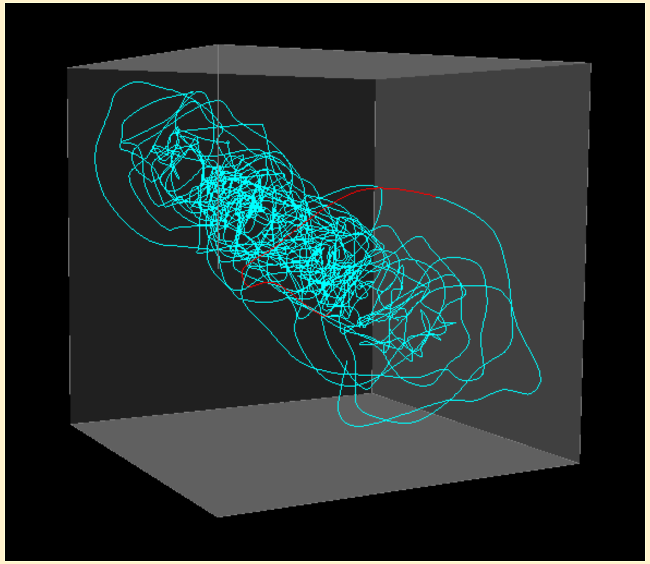
混沌搅拌器



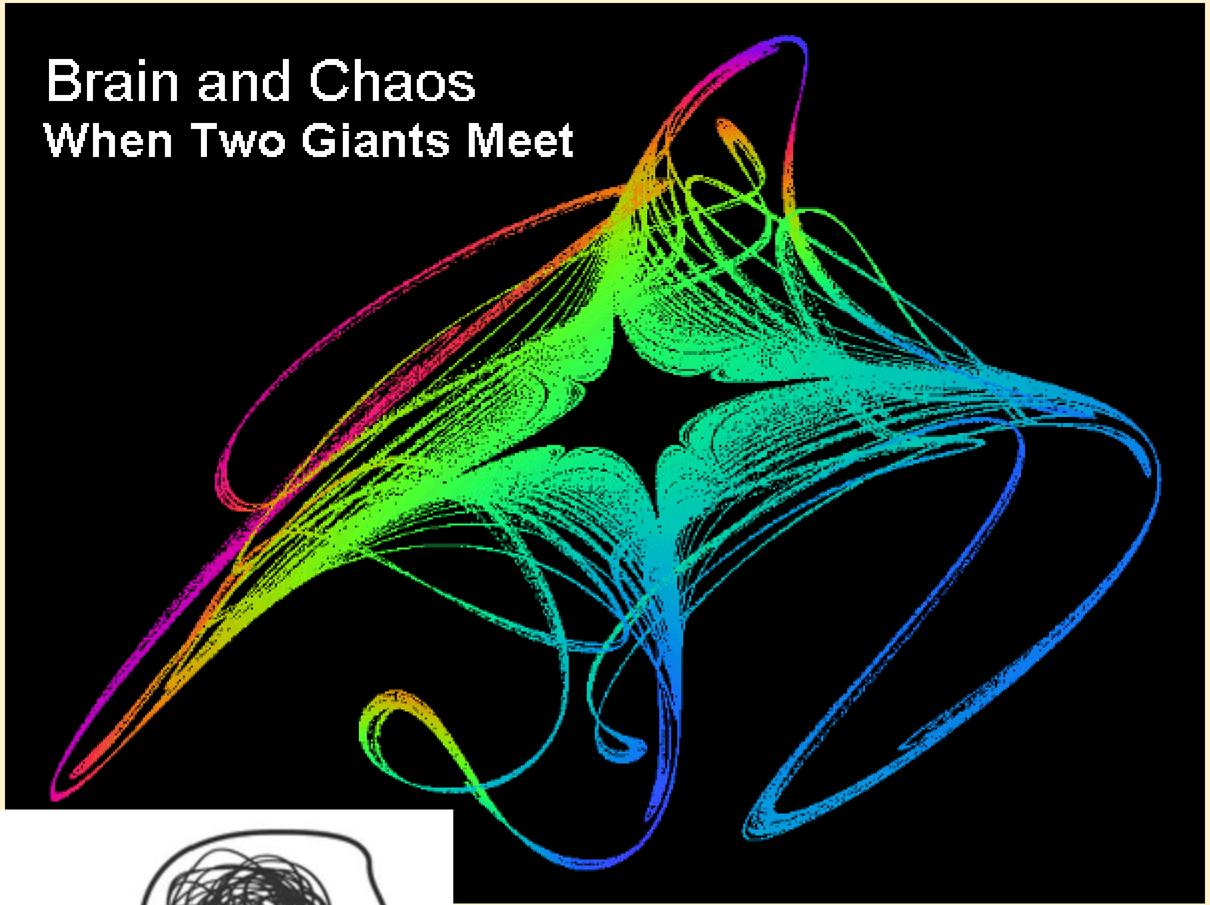


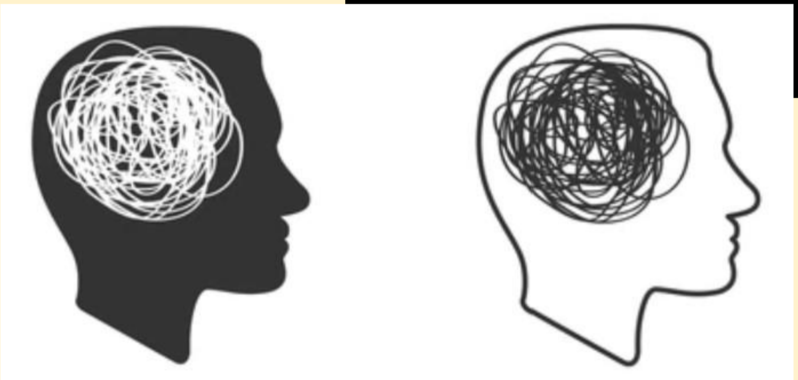
混沌喷水器

大脑与混沌



EEG



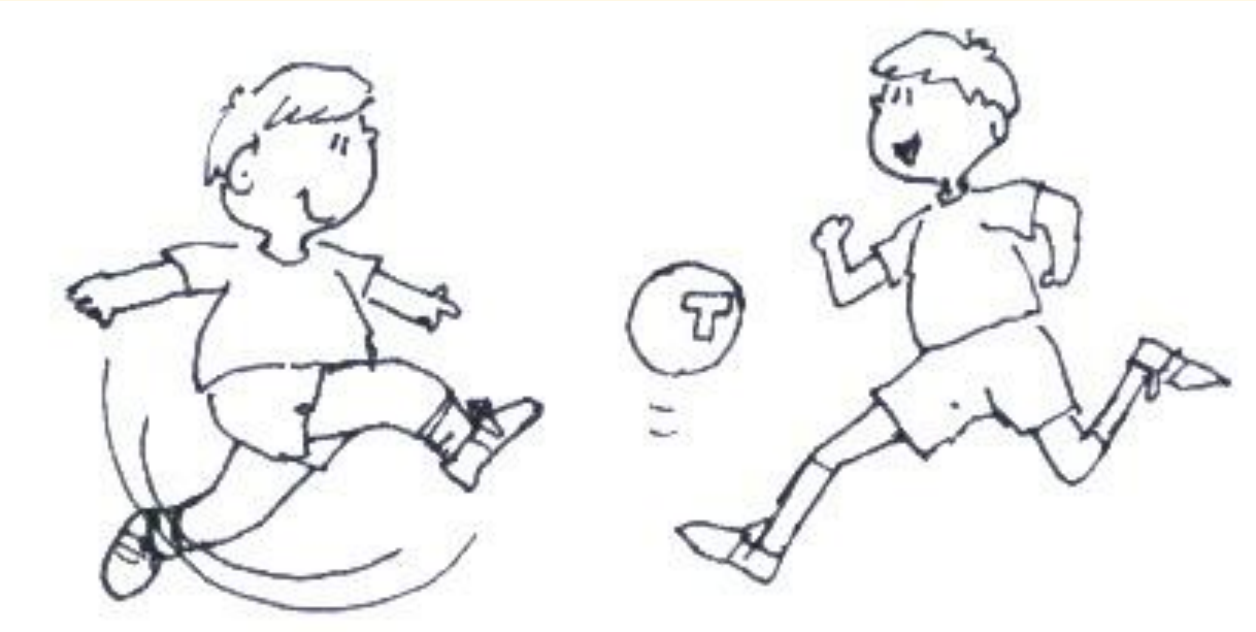


第7课（王青云）

离散混沌

三要素：　全局－　不收敛、不发散、非周期

局部－　收缩、　扩张、　返回



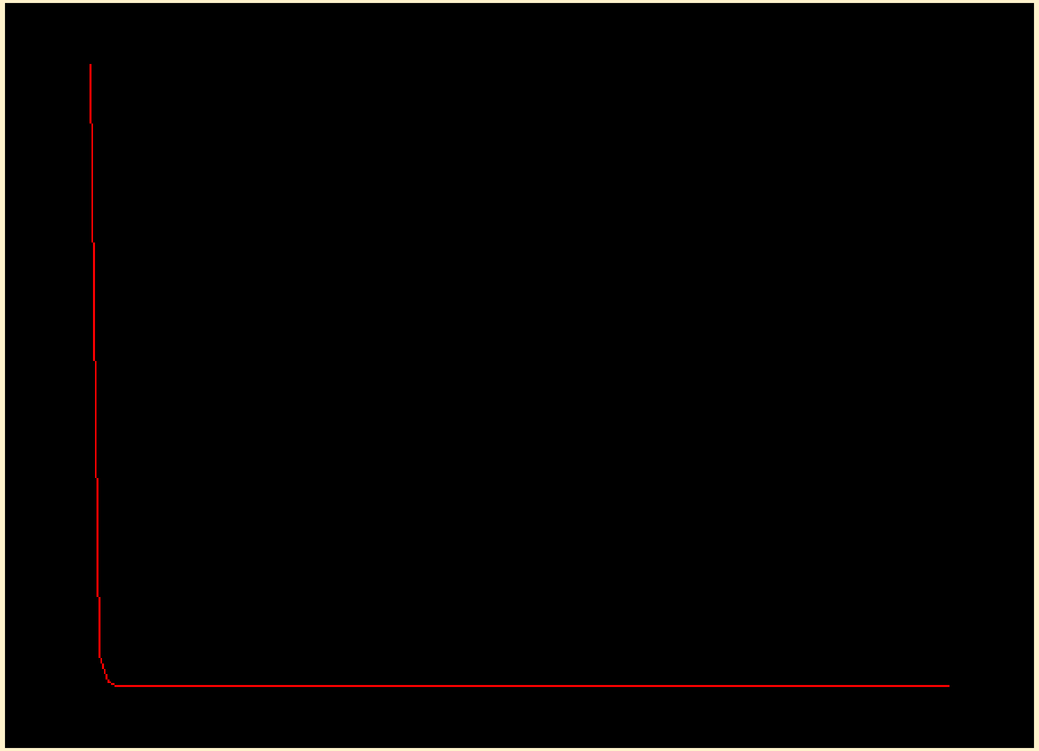
想一想：

皮球会怎样蹦？

往外踢	[不配合]	往里踢
不收敛	[非周期]	不发散

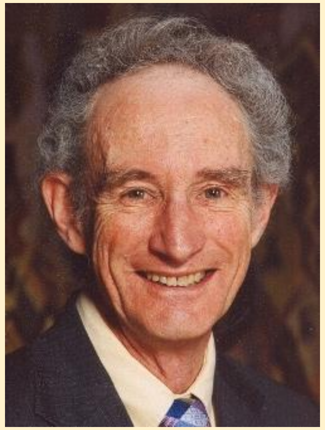
离散混沌：Logistic 映射

$$x(k+1) = \alpha\, x(k)[1 - x(k)]$$



R.M. May, ” ***Nature*** 261(5560): 459–67, 1976

R. M. May,” ***Science*** 197(4302): 463-465, 1977



Robert M. May

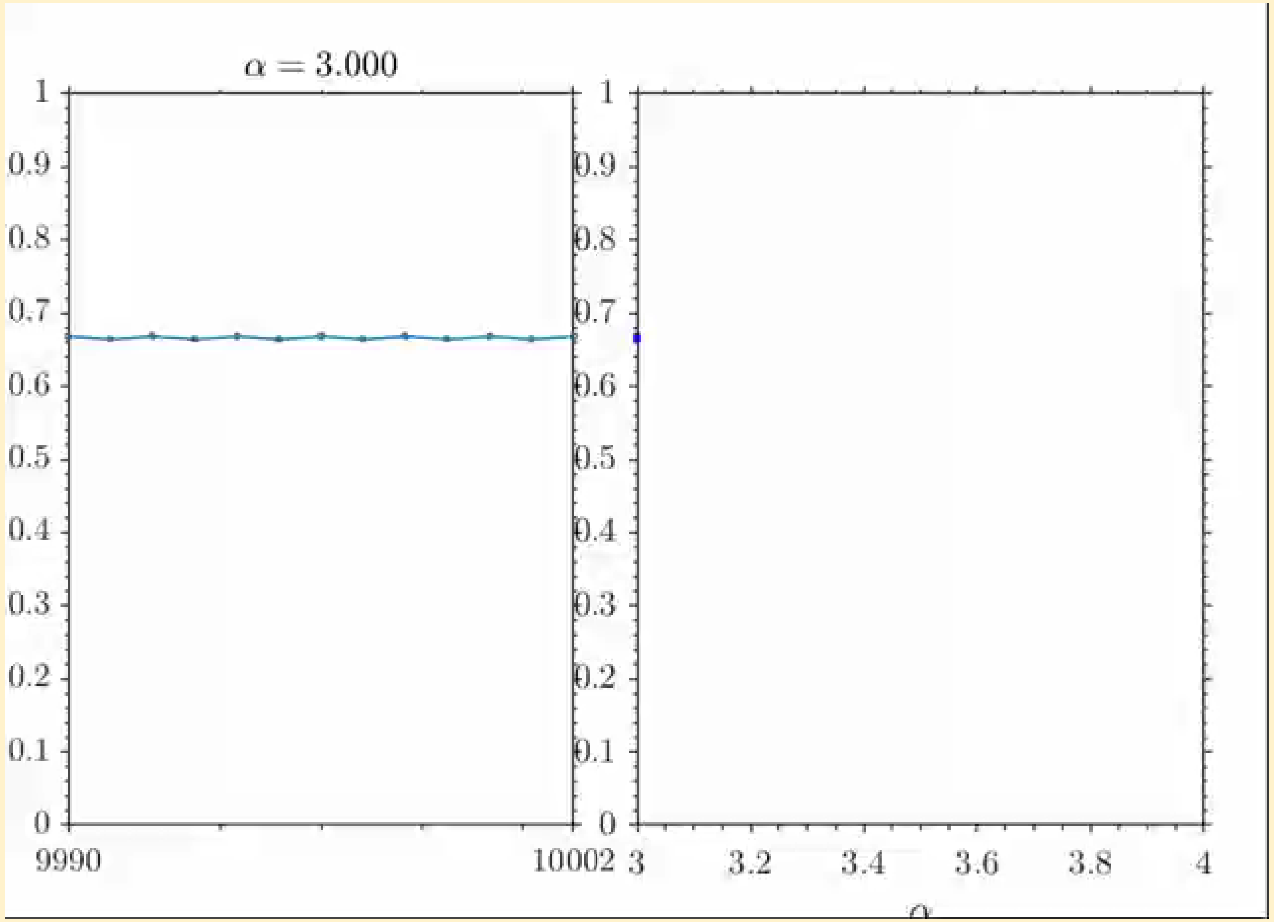
(1936 - 2020)

第4课（张旭）

第5课（马军）

Logistic Map

$$x(k+1) = \alpha\, x(k)[1 - x(k)]$$



Example:

λ = 3.3 → x(k+1) = 3.3 x(k) (1 – x(k))

Start from: k = 0

X(0) = 0.479

X(1) = 3.3 × 0.479 (1 – 0.479) = 0.824
X(2) = 3.3 × 0.824 (1 – 0.824) = 0.479

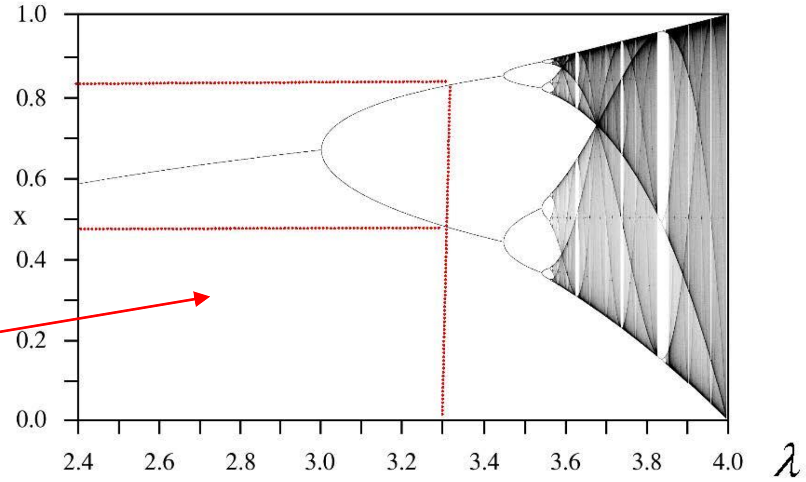
X(3) = 3.3 × 0.479 (1 – 0.479) = 0.824
X(4) = 3.3 × 0.824 (1 – 0.824) = 0.479

X(5) = 3.3 × 0.479 (1 – 0.479) = 0.824
X(6) = 3.3 × 0.824 (1 – 0.824) = 0.479

… …

Period 2: { 0.479, 0.824, 0.479, 0.824, 0.479, 0.824, 0.479, 0.824, … }

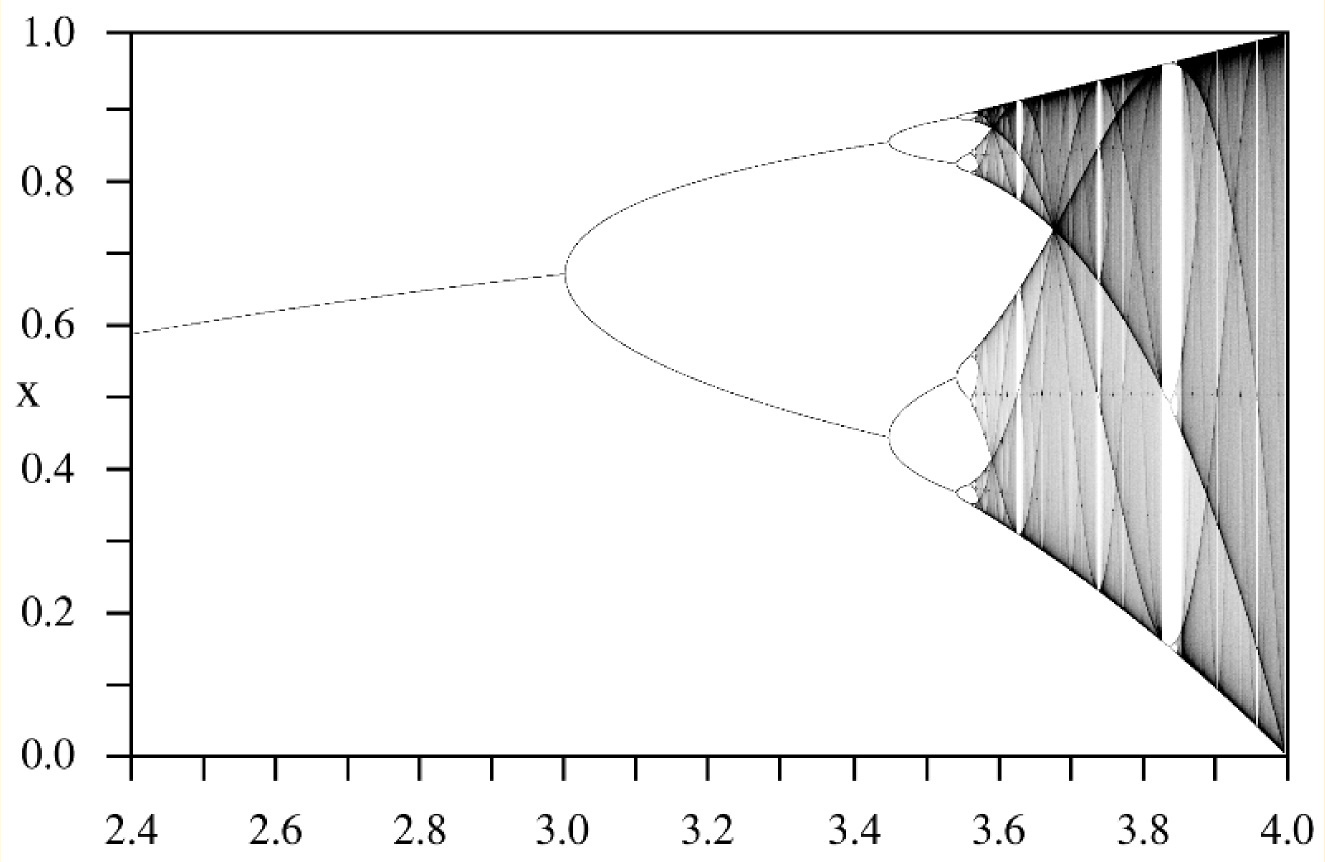
第7课（王青云）



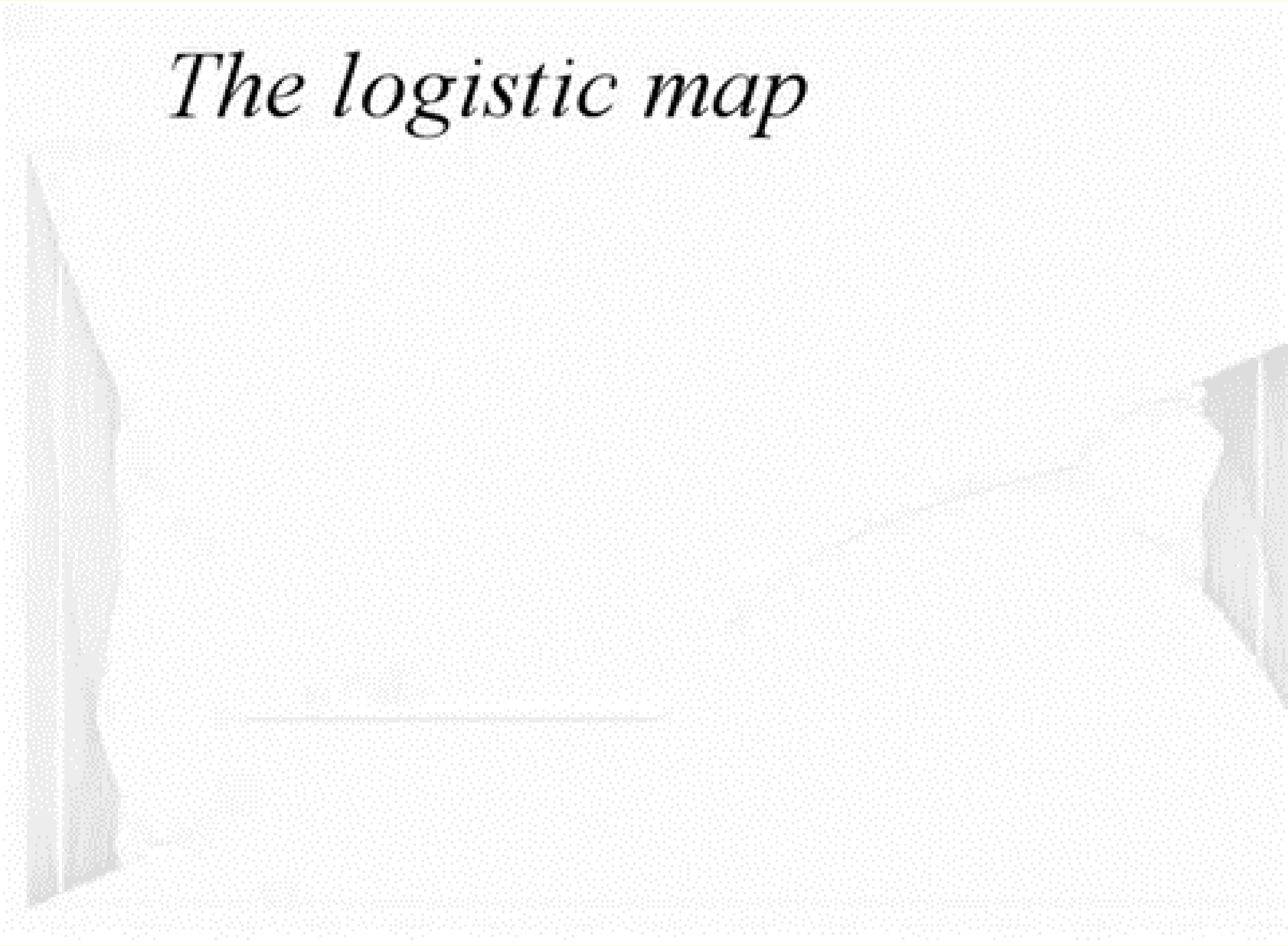
分叉

（周期倍分 → 混沌）

混沌映射特性：无穷多个周期解



Logistic Map has self-similarity – Fractal structure



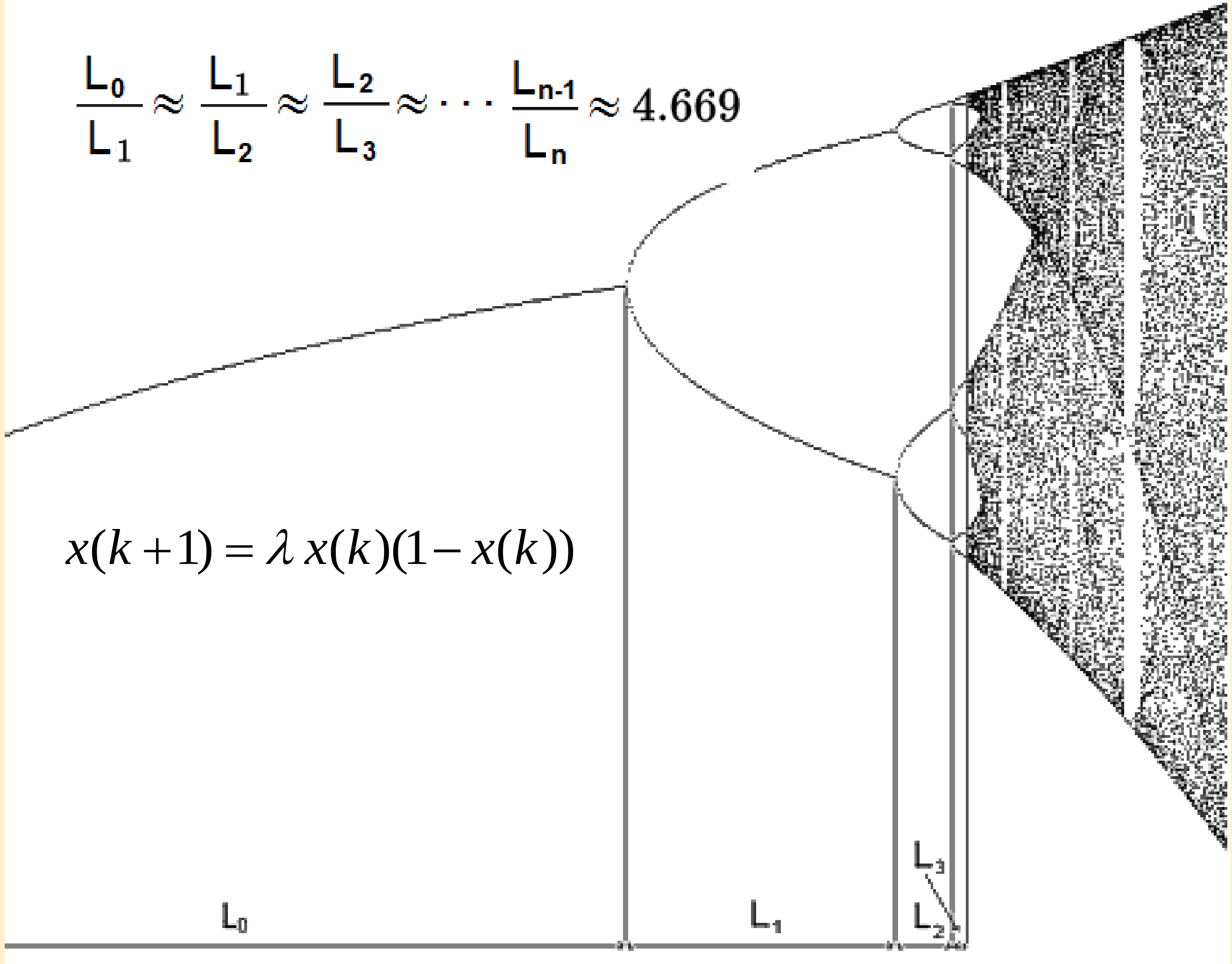
时空斑图生成

第5课（马军）

自相似性和分形结构

第6课（刘坚）

费根鲍姆 常数

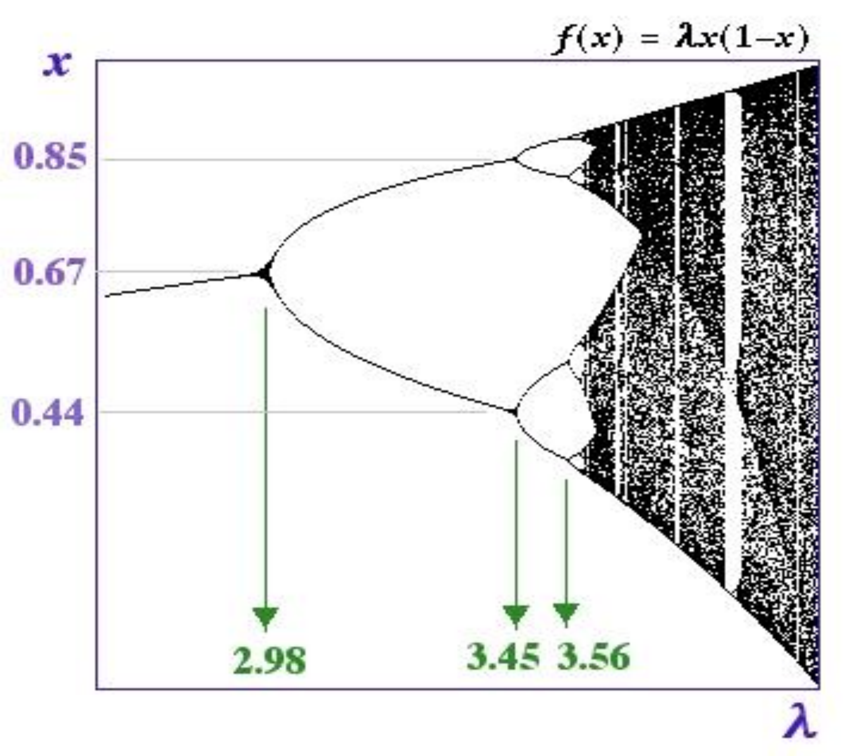


Mitchell Feigenbaum
(1944 -2019)

2010 Fashion Show in Tokyo

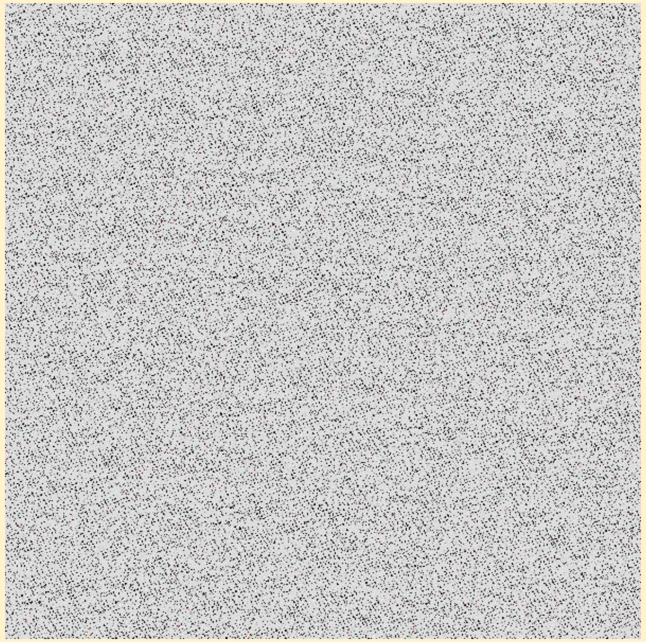
Courtesy of Kazu Aihara

混沌映射特性：遍历性



遍历

二维 Logistic 映射



遍历性 Ergodicity

混沌的遍历特性应用于图像加密

Fig. 1 Original Image

$$x(k+1) = 3.8x(k)[1 - x(k)]$$

$$x(0) \in (0,1)$$

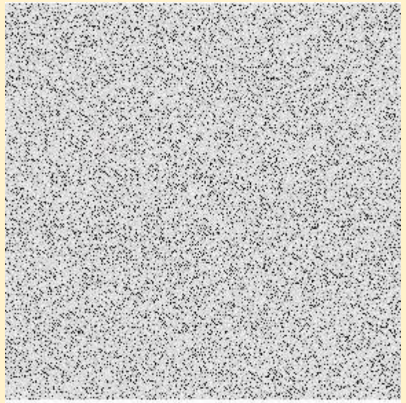


Fig. 2 Encrypted Image

正确的解密

不正确的解密

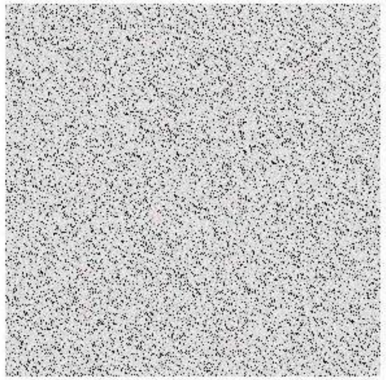
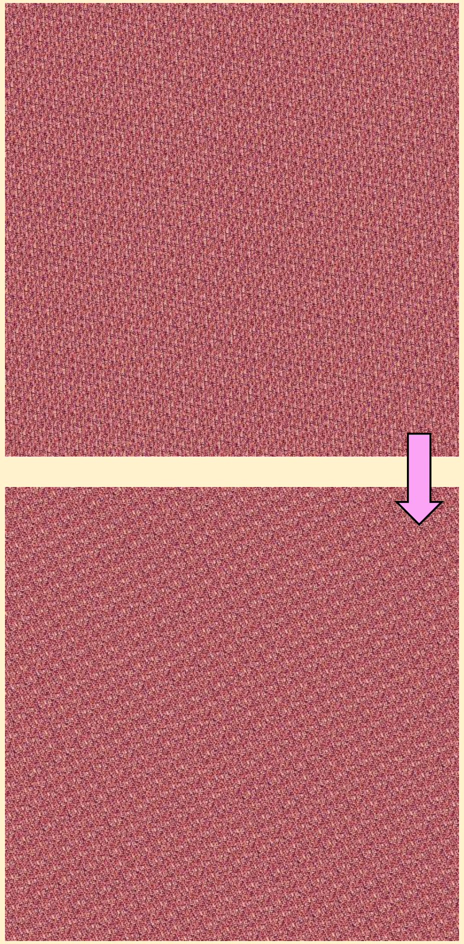


Fig. 3 "Detected" Image by an intruder who used the same software but missed one digit in the key

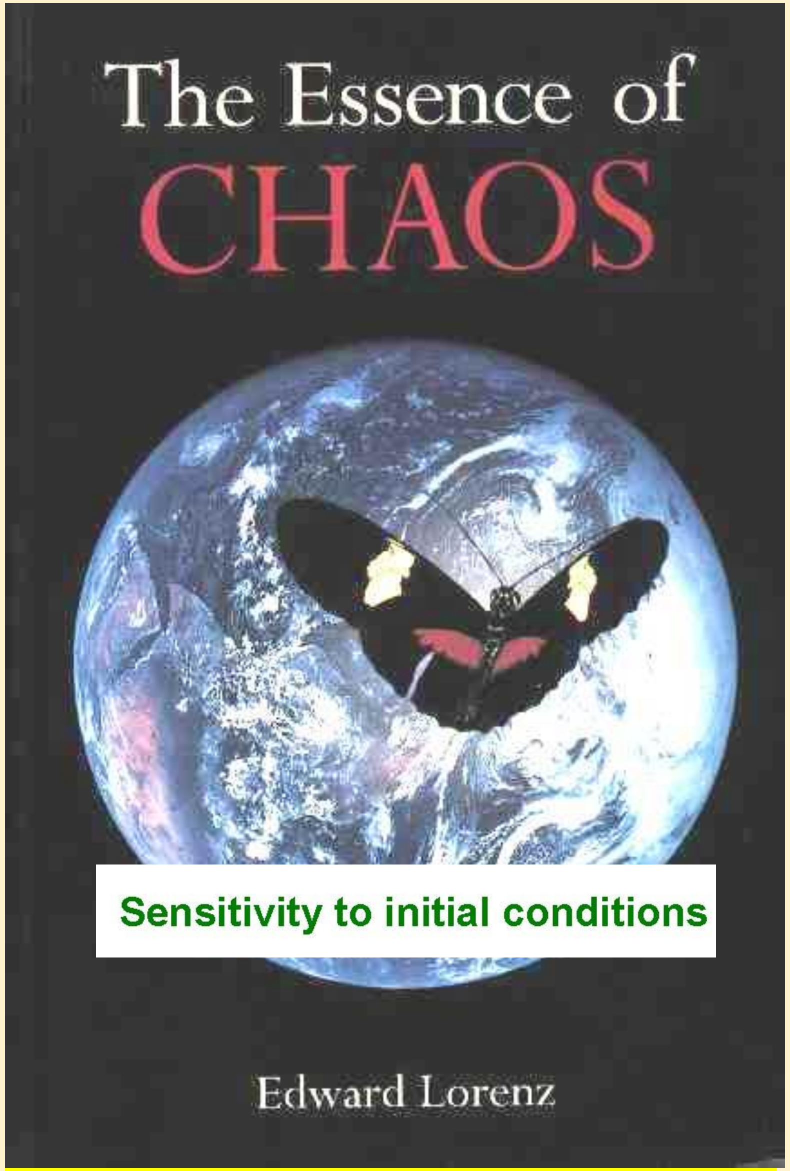
第8课（叶国栋）

混沌的遍历特性应用于图像加密



不正确的解密

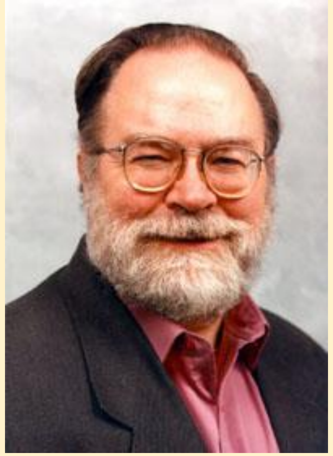
混沌对初始条件的敏感依赖特性



" ... a man sneezing in China may set people to shoveling snow in New York."

“一个人在中国打个喷嚏可能会让纽约的居民去铲雪。”

离散混沌数学理论的诞生



James A. Yorke

(1941-)

《美国数学月刊》

American Mathematical Monthly

- 1973年3月一个周五的下午，美国马里兰大学数学系里。时为博士生的李天岩来到了导师约克的办公室
- 约克：“ I’ve read Lorenz’s paper. Now, I have a good idea for you!”
- 李天岩：“Really? Is your idea good enough for the *Monthly*?”
- 约克：”Yes - 周期三意味着混沌”
- 李天岩两周后证明了： 约克的idea 是对的

Tien-Yien Li 李天岩

(1945-2020)

李-约克 定理

- 如果一个连续区间映射有一个周期为 3 的点，则这个函数也有一个周期为任意正整数 n 的点。
- 区间中存在不可数个初始点，函数从这些点出发的迭代点序列既不是周期的，又不趋向于任何周期轨道 → “序列的这种特殊状态很混沌 (chaotic)”

文章 “Period Three Implies Chaos” 写好后，真的寄给了《美国数学月刊》

文章被编辑退回：太具 “研究性”了吧？此文想在月刊上发表的话就得彻底改写！

于是文章在李天岩的桌上被搁置了将近一年 。。。

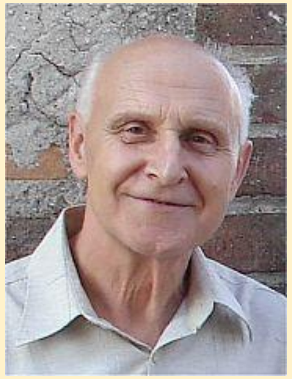
故事是这样完结的…

- 1973年是马里兰大学的“生物数学年”，Robert M May 被邀请做了历时一周的讲座。
- 他最后一天讲了令他困惑的 Logistic 映射。
- 约克送他去机场时把那篇关于李-约克定理的文章草稿给他看了。他看完之后大吃一惊，认定此定理完全解释了他的疑问。
- 约克回来后立即跑到李天岩的办公室，叫嚷道：“T Y！我们得马上改写这篇文章!”
- 于是文章在两个星期内改写完毕，三个月后被接收，同年刊登在《美国数学月刊》上。

该文第一次在数学和科学历史上使用了Chaos 这一名称，并第一次在数学上严格地引入了 Chaos 的定义。

后来发现，故事并没有完结 …

原来，乌克兰数学家沙可夫斯基 (Sharkovsky) 10年前早就已经证明了比李-约克定理第一部分更为一般的结果，1964年用俄文发表在西方人几乎看不到的俄语《乌克兰数学杂志》上。



Oleksandr M. Sharkovsky

(1936 - 2022)

"周期三意味着各种周期" 原来不是新的发现！

不过，沙可夫斯基的论文里没有 "Chaos"。

李-约克定理今天已经被简化了，核心在定理的第二部分 – Chaos

CHAOS 来到了中国

据说是北京大学朱照宣教授最先把 Chaos 翻译为“混沌”

这个翻译很好，同时也带来了很多与中国历史文化相关的故事 。。。

朱照宣

(1930年7月 -)

唐诗

《全唐诗》卷377

泛黄河

孟郊

谁开昆仑源，流出混沌河。
积雨飞作风，惊龙喷为波。
湘瑟飕飗弦，越宾呜咽歌。
有恨不可洗，虚此来经过。

黄河壶口

中国古代关于《混沌》的故事

古人想象，天地未开辟以前，宇宙是模糊一团的状态，称为“混沌”。

- 《太上老君八十一化图》之第二化：

  “... 空洞之中, 又生太无, 太无之内生玄元始三气, 三气相合，称为混沌。”

- 太上老君者，是道教之主：出乎太无之先，起乎无极之源，经历天地，不可称载，终乎无终，穷乎无穷者也 。

- 公元165年，边韶作《老子铭》，说 ：“世之好道者触类而长之，以老子离合于混沌之气，与三光为终始。”故此，道教的经书《老子想尔注》中说：“一散形为气，聚形为太上老君”。

- 也有一说，太上老君是由老子演变而来。

《老子·道德经》

老子（约公元前600-470年），春秋時代思想家。

- 《史记·老子韩非列传》：老子姓李名耳，字伯阳，又称老聃，楚国苦县（河南）人。在传说中，老子刚生下来时就有白色眉毛及胡子，所以被后人称为老子。
- 《老子章句》分为八十一章，前三十七章为《道经》，后四十四章为《德经》，故有《道德经》之名。
- 《道德经》第四十二章："道生一，一生二，二生三，三生万物，万物负阴而抱阳，冲气以为和。"
- 无名道化 (零) → 混沌元气 (一) → 阴阳二气 (二) → 阴阳之和 (三) → 天下万物

"Period three implies chaos"

《庄子·寓言》

庄子，姓庄名周，战国蒙县（河南商丘，或安徽蒙城）人氏。是继老子之后战国时期道家学派的主要代表人物。

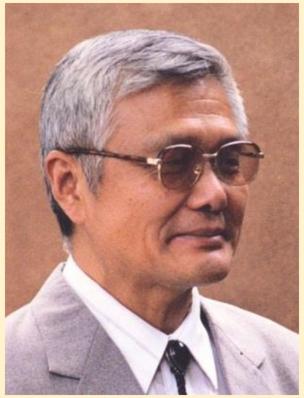
“一尺之锤，日取其半，万世不竭。”

庄生梦蝶一场空 – 不过，不是 Lorenz 蝴蝶。

(约公元前365-286年)

郝柏林教授在他的英文版《混沌》扉页，以及在《湍鉴—混沌理论与整体性科学导引》一书前言，都引过《庄子·应帝王》中一句话：

“南海之帝为倏，北海之帝为忽，中央之帝为浑沌。”（成语：倏忽之间 shū hū）



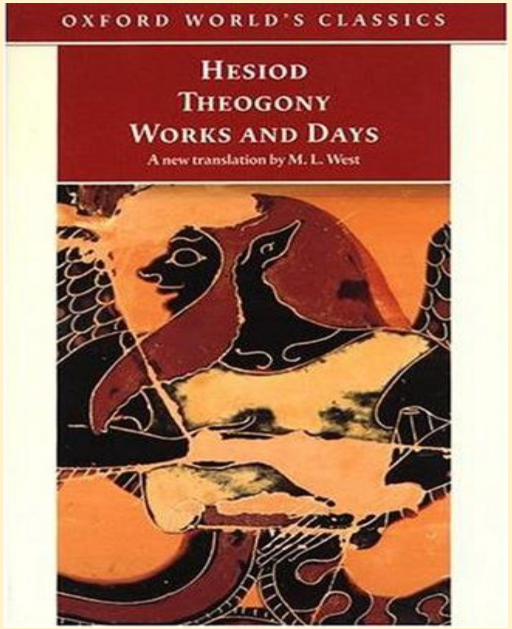
郝柏林

(1934-2018)

CHAOS 在欧洲

- 混沌一词在英、法、德文中写为 chaos，在俄文中写为 xaoc , 均源自希腊文 ΧΑΟΣ (χαοσ)。
- 西文中关于混沌的释义一般可追溯到古希腊农民诗人 Hesiod 所著的 Theogony，即名著《神谱》。
- Hesiod 对混沌的描述影响深远。亚里士多德曾肯定过《神谱》对混沌的看法：

  “Hesiod 在提出‘原始混沌’时所说的话看来是对的。万物之先有混沌，然后才产生了宽袤的大地。”



在希腊神话中，一切皆从混沌(Chaos)开始 ……

宇宙之初，只有混沌(Chaos)，它是一个无边无际、一无所有的空间。随后诞生了地母神盖亚(Gaea）、地狱深渊神塔耳塔洛斯(Tartarus）、黑暗神俄瑞波斯(Erebus）、黑夜女神尼克斯(Nyx）和爱神厄洛斯（Eros）…… 世界从此开始。

XAOΣ

古罗马诗人 Publius Ovidius Naso (约公元前43-后17年) 所著描写希腊和罗马神话故事的代表作 Metamorphosis 中，发挥了 Hesiod 对混沌的描写：

“天地未形，笼罩一切、充塞寰宇者，实为一相，今名之曰混沌。”

Publius Ovidius Naso 的一首名诗:

I’m sorry for any fool who rates sleep a prime blessing.
And enjoys it from dusk till dawn.
Night in, night out. What’s sleep but cold death’s reflection?

- 摘自‘Elegy 9b’(Peter Green 译)

《圣经》

- 《圣经》对混沌的描述最主要出现在《创世纪》中，后面的《约伯记》、《以赛亚书》、《耶利米书》以及《圣经·新约》中的《约翰一书》对混沌的诸多讨论都与此相关。

- 在《旧约》中混沌写作 tohu (英文意思是 confusion), 常与 bohu (英文意思是 void) 连用，合起来写成 tohuwabohu ，希腊文写作 χαοσ，英文译本中有多种译法，通常译为 Chaos

例子

《圣经》开篇：“起初，神创造天地。地是空虚混沌，
渊临黑暗；神的灵运行在水面上。”（《创世记》1:1,2）

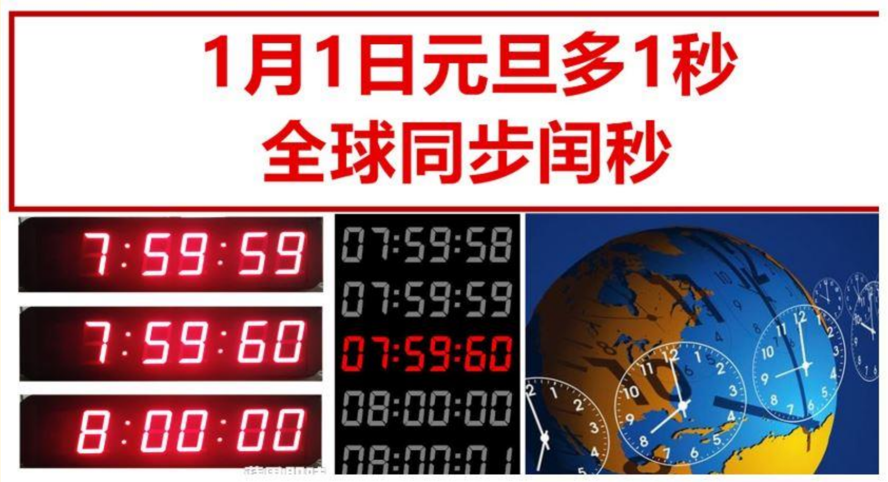
混沌的宇宙

形与数，都在天文学中；而天文学与诗为邻。 -- 雨果

天体运行在混沌中

NewScientist
28 February 2004
INSIDE
THE BEST JOBS IN SCIENCE
PLANETS IN CHAOS
Breakdown in Newton's clockwork universe
SPECIAL REPORT
SUPER FLU
Next-generation vaccines
The trouble with drugs
Should we make a killer strain?
£2.40 US$4.95 No2436

混沌的宇宙

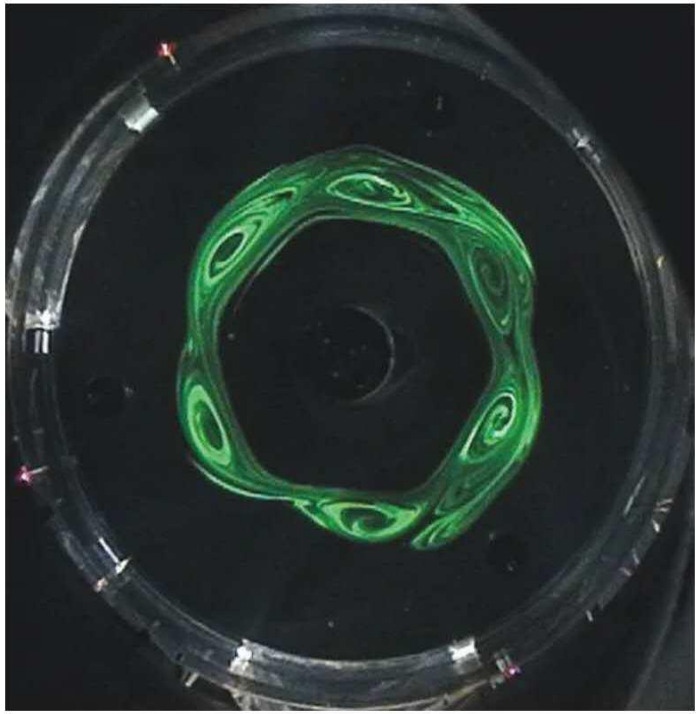


16亿年不差1秒的高精度钙离子光钟 | NSR

Original 《国家科学评论》 中国科学杂志社 Today

在宇宙尺度下，没有数学上严格周期运动的天体

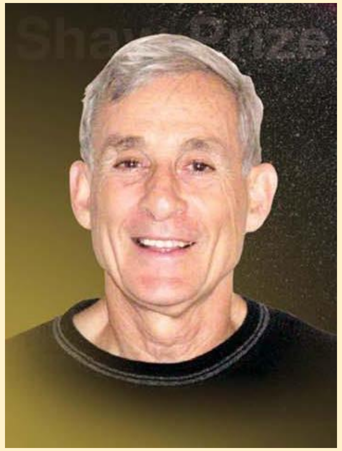
2010年3月，美国国家航空航天局发布的图片显示，一个奇异的六边 形云团环绕着土星北极，其容积相当于四个地球那么大。这个图案吸引了以美国航空航天局卡西尼（Cassini）太空计划科学家们的兴趣。自从 26年前被旅行者号飞船发现后，这个六边形相对于土星的自转率和轴线似乎保持不变。



目前，天文学家对这个六边形还没有一个完美的解释，但他们已经在实验室里做出了这个自然现象的模拟。

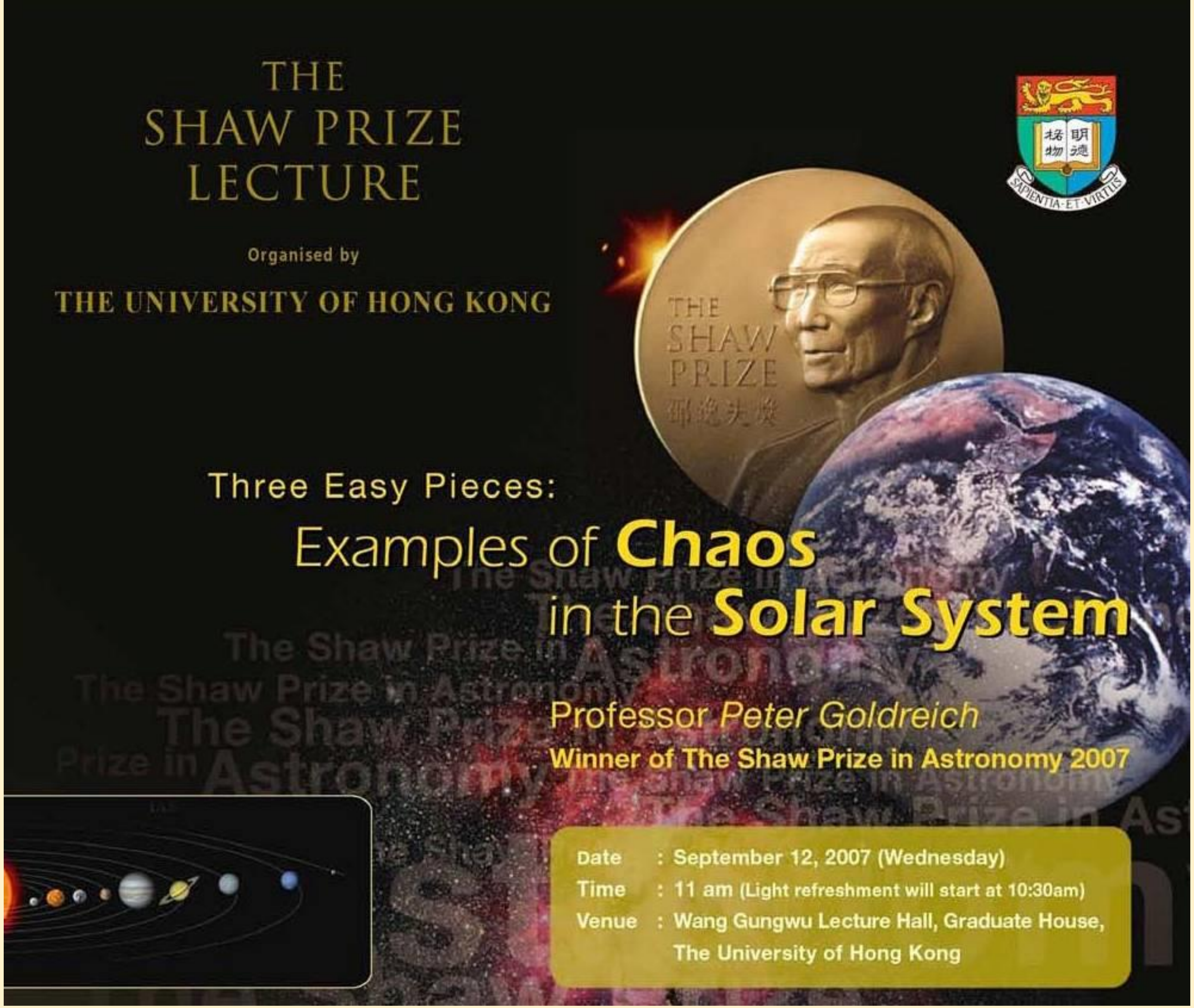
混沌的宇宙

2007年的中国邵逸夫天文奖颁发给了普林斯顿大学的天文学家 Peter Goldreich，以彰其于天文物理学及行星科学之贡献。他的主要贡献是在 “轨道共振” 和 “行星环” 方面的研究。他认为太阳系行星的共振是混沌的；混沌决定了太阳系行星的形成，导致地球上的某些 “生物种类灭绝” 甚至某些天体的 “物质消亡”，让天体的 “牛顿时钟” 最终趋于混沌。



(1939 -)

- Peterson, Newton's Clock: Chaos in the Solar System, 1993
黄启明.黄铭锵(译):《牛顿时钟：浑沌太阳系》1997

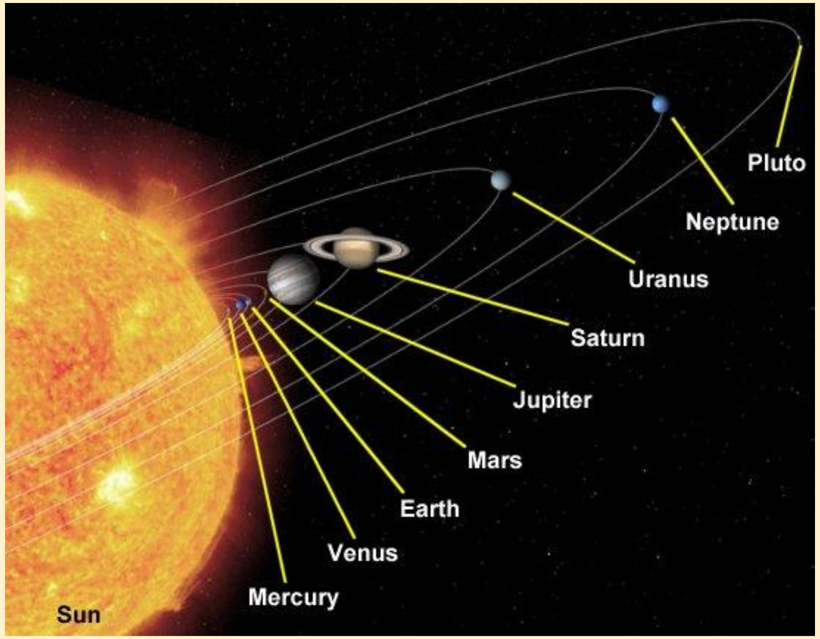

THE
SHAW PRIZE
LECTURE
Organised by
THE UNIVERSITY OF HONG KONG
SAPIENTIA · ET · VIRTUS
THE SHAW PRIZE
Three Easy Pieces:
Examples of Chaos
in the Solar System
Professor Peter Goldreich
Winner of The Shaw Prize in Astronomy 2007
Date : September 12, 2007 (Wednesday)
Time : 11 am (Light refreshment will start at 10:30am)
Venue : Wang Gungwu Lecture Hall, Graduate House,
The University of Hong Kong

混沌的宇宙

科学家认为，整个宇宙中大概有五千亿个星际云（银河系）。我们的太阳和九大行星，大约46亿年前几乎在同一时间从同一个星际云的一次突然灾变中诞生。这种由微小的扰动而引发的巨大无比的突变目前可以也只能用混沌理论来解释。

* J. J. Lissauer, Chaotic motion in the Solar System, Reviews of Modern Physics, 71(3): 835-845, 1999.

* J. Laskar, On the Spacing of Planetary Systems, Physical Review Letters, 84: 3240-3243, 2000.



混沌的宇宙

是否所有的行星轨道最终都趋向于混沌呢?

美国天文学会 2006 年 Brouwer 奖获得者、法国著名天文学家 Jacques Laskar 在 1989 年 Nature 上发表了他非常精确的（有15万个单项的方程组）、基于实际数据的预测，指出 2 亿年后太阳系所有行星（包括地球）的轨道最终会变成是混沌的。

[2009年邵逸夫天文奖得主徐遐生也曾于1996年获得过 Brouwer 奖]

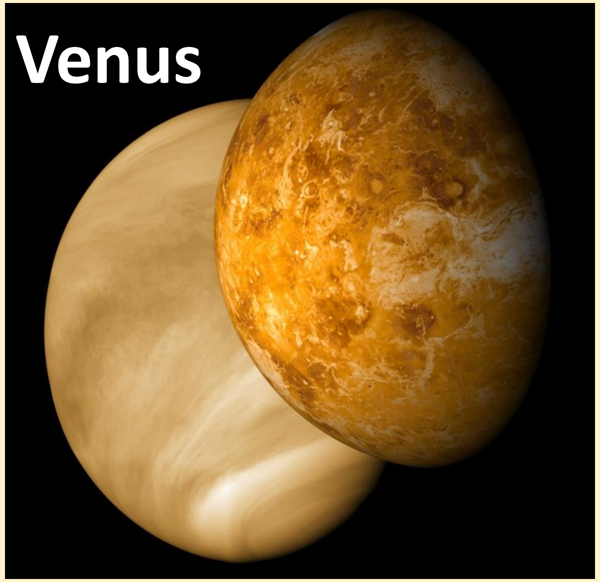
J. Laskar, A numerical experiment on the chaotic behaviour of the solar system, Nature, 338: 237-8, 1989.

J. Laskar, Large scale chaos and the spacing of the inner planets, Astronomy and Astrophysics, 317: 75-78, 1997.

太阳系

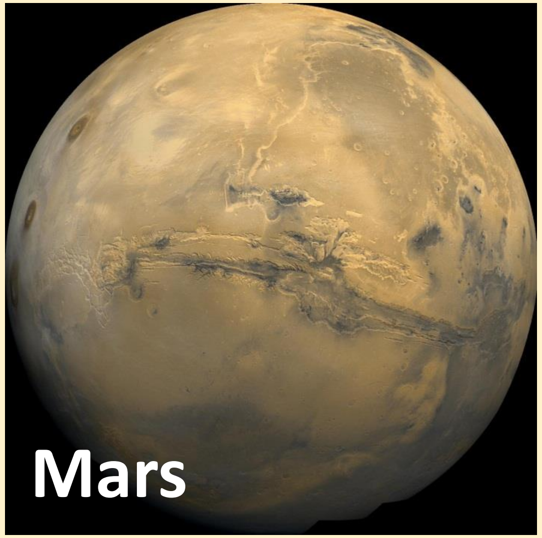
我们的行星邻居

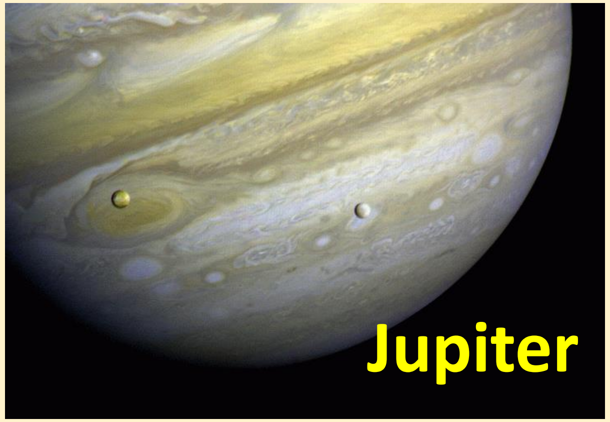
金星



地球

火星

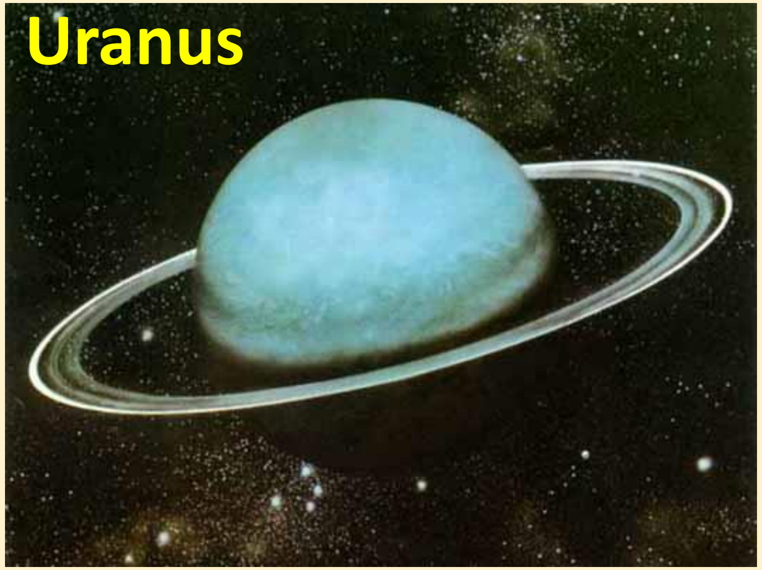


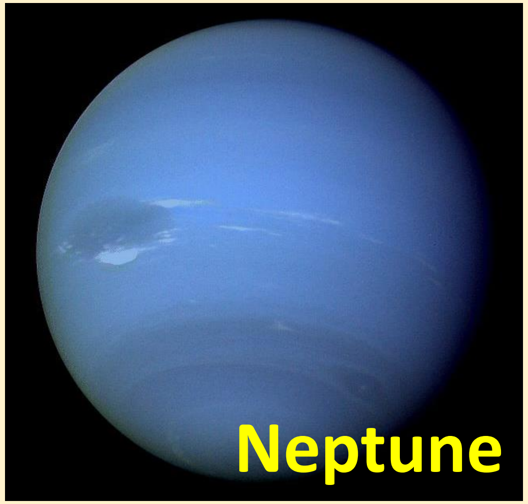


木星

土星

天王星





海王星

早期的太阳系

Download full size image

Early Solar System May Have Been Chaotic Place

Posted on: Thursday, 26 May 2005, 00:50 CDT

Astrobiology Magazine -- People of every culture have been fascinated by the dark "spots" on the Moon, which seem to compose the figure of a rabbit, frogs or the face of a clown. With the Apollo missions, scientists found that these features are actually huge impact basins that were flooded with now-solidified lava.

One surprise was that these basins formed relatively late in the history of the early solar system -- approximately 700 million years after the formation of the Earth and Moon. Many scientists now believe that these lunar impact basins bear witness to a huge spike in the bombardment rate of the planets – called the late heavy bombardment (LHB). The cause of such an intense bombardment, however, is considered by many to be one of the best-preserved mysteries of solar system history.

In a series of three papers published in this week's issue of the journal Nature, an international team of planetary scientists, Rodney Gomes (National Observatory of Brazil), Harold Levison (Southwest Research Institute, United States), Alessandro Morbidelli (Observatoire de la Côte d'Azur, France) and Kleomenis Tsiganis (OCA and University of Thessaloniki, Greece) -- brought together by a visitor program hosted at the Observatoire de la Côte d'Azur in Nice – proposed a model that not only naturally solves the mystery of the origin of the LHB, but also explains many of the observed characteristics of the outer planetary system.

现在的太阳系

Performing your original search, **Science 283, 1877**, in *Science* will retrieve 90 results.

Science 19 March 1999:
Vol. 283. no. 5409, pp. 1877 - 1881
DOI: 10.1126/science.283.5409.1877

RESEARCH ARTICLES

The Origin

N. Murray, [1] M

Classical analy
resolved by a n
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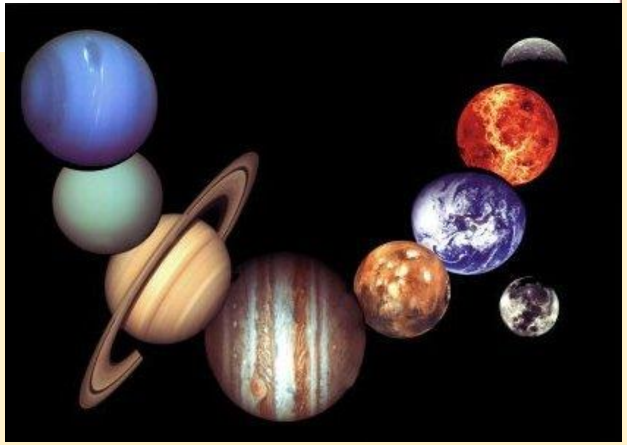
From the Academy

Chaos and stability of the solar system

Renu Malhotra*†, Matthew Holman‡, and Takashi Ito§

*University of Arizona, Tucson, AZ 85721; ‡Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138; and §National Astronomical Observatory, Tokyo 181, Japan

Over the last two decades, there has come about a recognition that chaotic dynamics is pervasive in the solar system. We now understand that the orbits of small members of the solar system—asteroids, comets, and interplanetary dust—are chaotic and undergo large changes on geological time scales. Are the major planets' orbits also chaotic? The answer is not straightforward, and the subtleties have prompted new questions.



现在的太阳系

From the Academy

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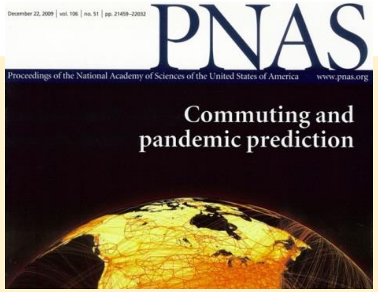
We also ask, how typical is our planetary system in the galaxy? What are the characteristics of a *stable* planetary system or of one that harbors a habitable planet?

In the last two decades remarkable advances in digital computer speed, the development of new numerical techniques, and the

This paper is a summary of a session presented at the third annual Japanese–American Frontiers of Science symposium, held September 22–24, 2000, at the Arnold and Mabel Beckman Center of the National Academies of Science and Engineering in Irvine, CA.

†To whom reprint requests should be addressed. E-mail: renu@lpl.arizona.edu.

12342–12343 | PNAS | October 23, 2001 | vol. 98 | no. 22 www.pnas.org/cgi/doi/10.1073/pnas.231384098



太阳系里的小星星

例如水星和土星的小月亮卫星

letters to nature

Chaos-assisted capture of irregular moons

Sergey A. Astakhov*, Andrew D. Burbanks†, Stephen Wiggins† & David Farrelly*

** Department of Chemistry & Biochemistry, Utah State University, Logan, Utah 84322-0300, USA*
† School of Mathematics, University of Bristol, Bristol BS8 1TW, UK

It has been thought[1–3] that the capture of irregular moons—with non-circular orbits—by giant planets occurs by a process in which they are first temporarily trapped by gravity inside the planet's Hill sphere (the region where planetary gravity dominates over solar tides[4]). The capture of the moons is then made permanent by dissipative energy loss (for example, gas drag[3]) or planetary growth[2]. But the observed distributions of orbital inclinations, which now include numerous newly discovered moons[5–8], cannot be explained using current models. Here we show that irregular satellites are captured in a thin spatial region where orbits are chaotic[9], and that the resulting orbit is either prograde or retrograde depending on the initial energy. Dissipation then switches these long-lived chaotic orbits[10] into nearby regular (non-chaotic) zones from which escape is impossible. The chaotic layer therefore dictates the final inclinations of the captured moons. We confirm this with three-dimensional Monte Carlo simulations that include nebular drag[3,4,11], and find good agreement with the observed inclination distributions of irregular moons at Jupiter[7] and Saturn[8]. In particular, Saturn has more prograde irregular moons than Jupiter, which we can explain as a result of the chaotic prograde progenitors being more efficiently swept away from Jupiter by its galilean moons.

Neptune Trojan

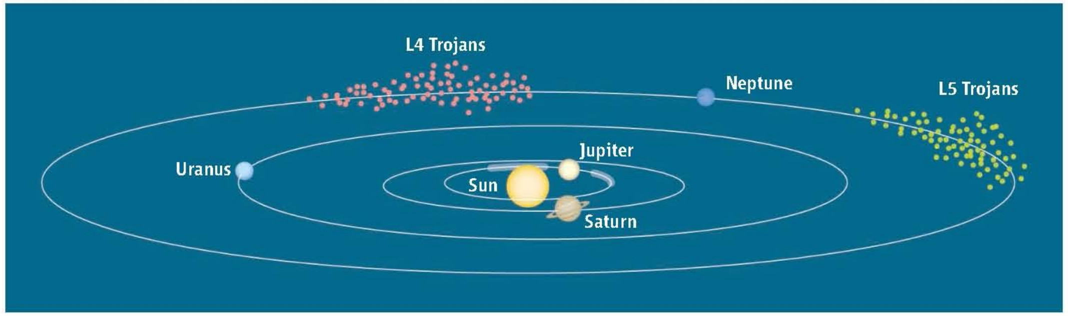
海王星特洛伊

Puzzling Neptune Trojans

An asteroid has been found in a highly inclined path co-orbiting with Neptune. Its discovery may help explain the evolution of the outer solar system.

Francesco Marzari

Trojan asteroids are small bodies that revolve about the Sun at the same distance as their host planet and share the planet's orbital path. They are locked at the two gravitationally stable locations, called triangular Lagrangian points, in distinct clouds that lead or trail the planet by about 60° (see the figure). Jupiter has the most of these Trojans, which are small rocky-icy bodies with diameters less than 300 km and are similar in composition to other minor bodies such as short-period comets, Kuiper Belt objects (KBOs), and Centaurs, small bodies that orbit between Jupiter and Neptune. About 2000 Jupiter Trojans are known today, but astronomers believe there may be as many of these asteroids in the kilometer-size range as there are main-belt asteroids (*1*). Four asteroids are also known to orbit in the Lagrangian points for Mars; these might possibly be rare remnants of planetesimals that formed in the terrestrial planet region. Moreover, Trojans are now known to gather near Neptune, and on page 511 of this issue, Sheppard and Trujillo report the discovery of the fourth such object (*2*), with important implications for theories of solar system formation.



Unusual asteroids. Trojan asteroids, small bodies that co-orbit with a planet in stable leading or trailing locations, are known to accompany Jupiter. They have also been discovered near Neptune, and Sheppard and Trujillo have now identified one with a highly inclined orbit.

Scientists theorize that Trojans are pristine bodies that originated very early in the history of the solar system and were captured in the final phase of planet formation. Different theories, not necessarily mutually exclusive, have been proposed to explain how planetesimals passing close to a planet fall into the force traps around the Lagrangian points. Among these are broadening of the tadpole-shaped regions of stable Trojan motion around the triangular Lagrangian points because of the growth of the planet's mass, direct collisional placement, drag-driven capture in the presence of the gaseous nebula, and chaotic trapping during giant planet migration (see below). There is as yet no general consensus on the source region of putative Trojans in the planetesimal disk. Some capture mechanisms demand that they formed near the planet's orbit, thus reflecting the physical and chemical composition of the planetary building blocks. The recent theory of chaotic capture, suggesting that planetesimals in temporary Trojan trajectories can be frozen into stable orbits as soon as planetary migration drives the host planet far away from a dynamically perturbed region (*3*), opens the possibility that Trojans might have formed in more distant regions of the planetesimal disk of the early solar system, sharing the same environment as KBOs.

“在巨大行星迁移运动过程中陷入混沌状态”

In the course of the Deep Ecliptic Survey, a NASA-funded survey of the outer solar system, astronomers announced in 2001 the discovery of the first known member of a long-sought population of bodies: the Neptune Trojans. Sheppard and Trujillo report the discovery of the fourth object in this group, which is noteworthy in that it exhibits a high inclined orbit (about 25°). This finding strongly supports the idea that Neptune Trojans fill a thick disk with a population comparable to, or even larger than, that of Jupiter Trojans. At the same time, the discovery puts constraints on the mechanism by which they were captured.

What makes the Neptune Trojans so special for astronomers? According to recent theories, the outer solar system might have been a tumultuous environment. During the last stage of planetary formation, the giant planets may have migrated away from their formation sites by exchanging angular momentum with the residual planetesimal disk. Jupiter drifted inward, although only slightly, whereas Saturn, Uranus, and Neptune migrated outward by larger amounts. This past planetary migration explains many of the observable characteristics of KBOs, in particular of the resonant ones called Plutinos. However, the migration

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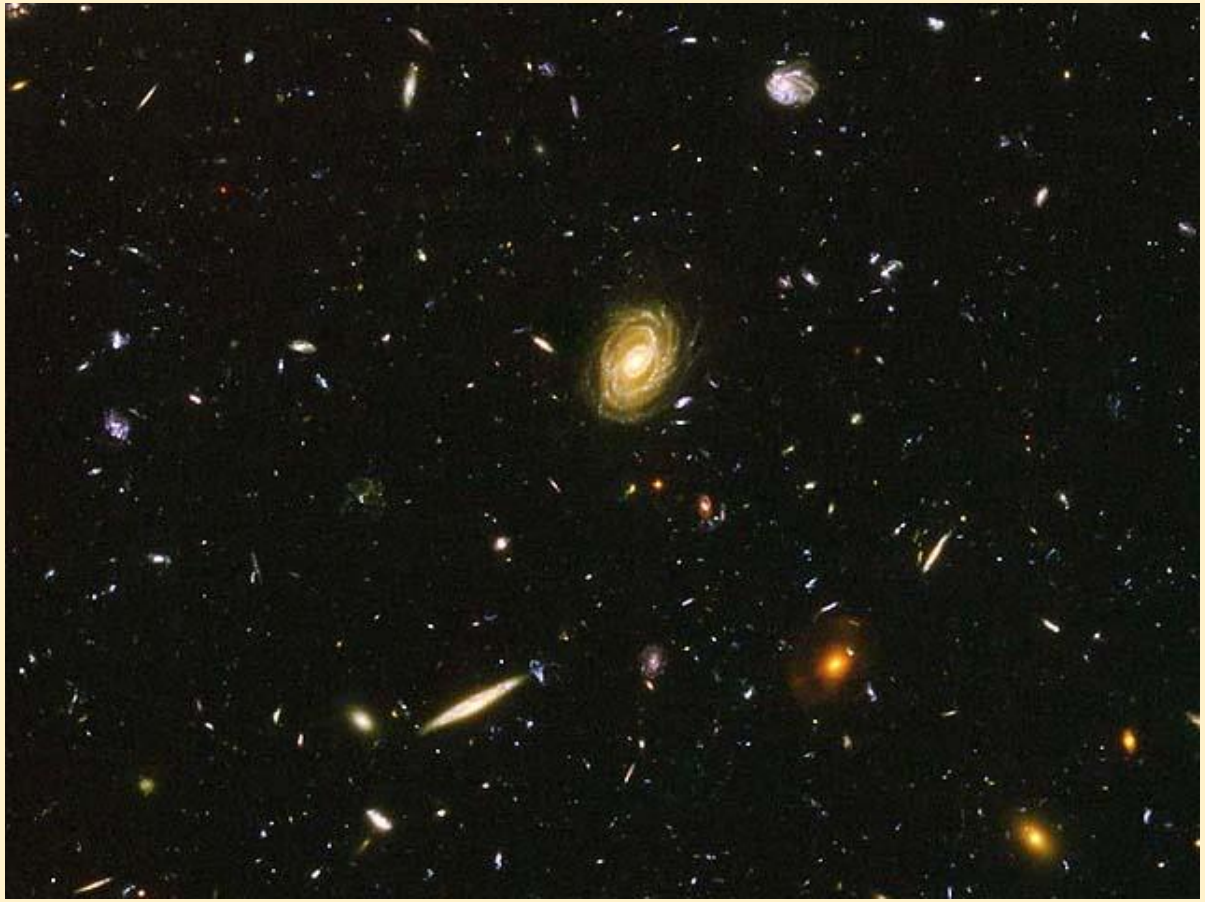
CREDIT: P. HUEY/SCIENCE

Kuiper Belt Objects - 柯伊伯带（海王星外侧）

远离太阳系以外 。。。



我们还有很多远方的朋友

远离太阳系以外。。。

目前科学家利用探测器所观察到的宇宙范围是 930 亿光年，这个范围也被称作“可观测宇宙”，其内部含有两万万亿个银河系这样大小的星系，而银河系内含有的恒星数量就超过了 4000 亿颗，可想而知，整个宇宙是多么的浩瀚。

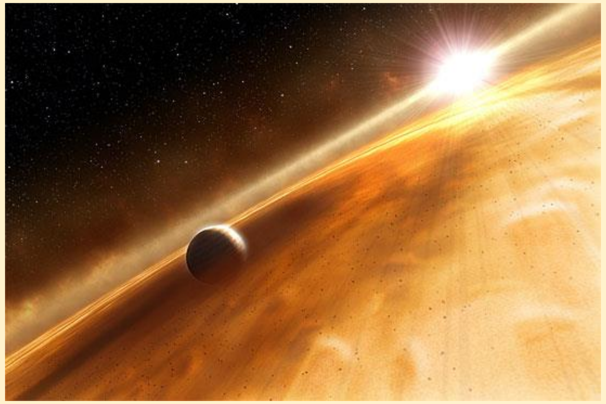
但人类不要说走出可观测宇宙，就算走出太阳系也几乎是一件不可能的事。太阳系的直径大约为 2 光年，对于银河系十万光年的直径而言，太阳系就如同一颗乒乓球放进了足球场里。而人类于上个世纪 70 年代末发射的探测器旅行者一号以及旅行者二号在宇宙中飞行了四十多年，至今都还在太阳系的边缘徘徊着。

- 刘亚东 光速为什么会被限制？[来源：微信公号“宇宙奥秘”2019]

太阳系外行星

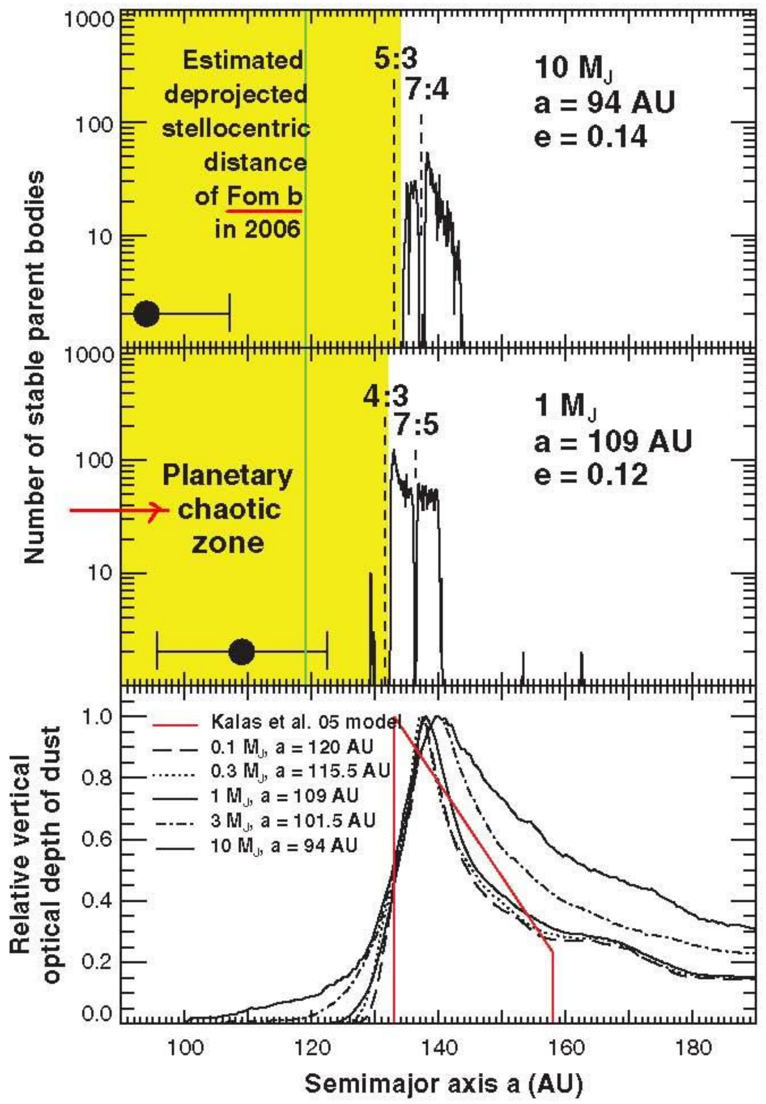
北落师门b (Fomalhaut b)是在南鱼座距离地球大约25 光年的一颗行星。

这颗行星是研究人员对这个系统经历了 8 年的审查之后，最终在 2008 年哈勃太空望远镜的照片中才发现的。



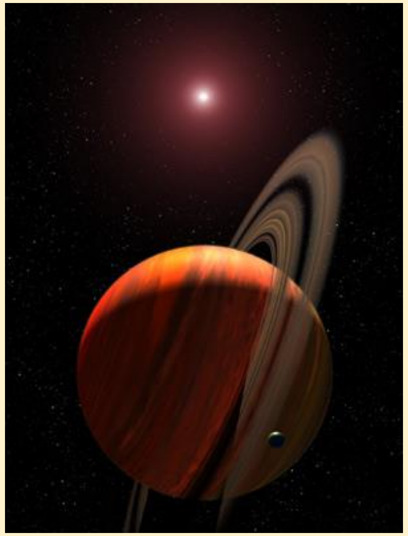
Fomalhaut b

Fig. 2. Dynamical models of how Fomalhaut b gravitationally sculpts the belt [see also (*15*)]. (**Top** and **middle**) Histograms of time-averaged semimajor axes of parent bodies that survive 100-My integrations with Fomalhaut b, whose parameters are chosen to reproduce the belt's inner edge at 133 AU and ellipticity of 0.11. Parent bodies are evacuated from Fomalhaut b's chaotic zone (yellow region). Gaps open at the planet's resonances, akin to the solar system's Kirkwood gaps. Black circles and bars mark the range of stellocentric distances spanned by the model orbits for Fomalhaut b. The apocentric distance for 10 M_J is inconsistent with the observed stellocentric distance of Fomalhaut b (green line). The 1-M_J model is consistent. (**Bottom**) Vertical optical depth profiles of dust generated from parent bodies. The planet orbit is tuned so that the optical depth is at half maximum at 133 AU, the location of the inner edge of the scattered-light model from (*6*) (red curve), which itself is an idealized and non-unique fit to the HST data. Although the dynamical and scattered-light models do not agree perfectly, lower planet masses are still inferred because they do not produce broad tails of emission at *a* > ~140 AU. At *a* > ~160 AU, the HST data are too uncertain to constrain any model.



太阳系外行星

Gliese 22: 天秤座，离地球约33光年



Gliese 22

Monografías de la Real Academia de Ciencias de Zaragoza **32**, 65–73, (2009).

Long-term stability for the Bb planetary-like object in the triple stellar system Gl 22

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Abstract

We analyse the long-term stability for a planetary-like object (16 M_J) recently discovered orbiting the B component in the hierarchical system of three low-mass stars Gl 22 AB. A complete solution for the planetary orbit assuming an approximately coplanar and circular orbit has been obtained.

As regards the planet-like object stability, carried out by means of a (2+2)-body model, we observe a behaviour that suggests that although for a relatively long time the motion looks stable, we can not discard that it could became chaotic later.

太阳系外行星

天鹅座16（16 Cygni）

位于天鹅座的三合星系统，
距离地球约70光年

16 Cygni

letters to nature

Chaotic variations in the eccentricity of the planet orbiting 16 Cygni B

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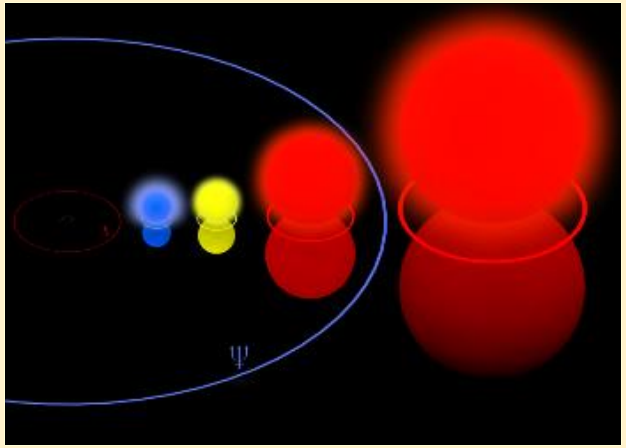
The planet recently discovered[1] orbiting the star 16 Cyg B has the largest eccentricity ($e = 0.67$) of any known planet. Planets that form in circumstellar disks are expected to have nearly circular orbits, although gravitational interactions in a system of two or more planets could generate high-eccentricity orbits[2,3]. Here we suggest that the eccentric orbit of 16 Cyg Bb arises from gravitational interactions with the distant companion star, 16 Cyg A. Assuming that 16 Cyg Bb formed in a nearly circular orbit, with the orbital plane inclined between 45° and 135° to the orbital plane of 16 Cyg A, and that there are no other planets with a mass similar to that of Jupiter within 30 astronomical units (AU, the average distance between the Earth and the Sun), then 16 Cyg Bb will oscillate between low-eccentricity and high-eccentricity orbits. The transitions between these orbits should occur every 10^7–10^9 years, with the planet spending up to 35 per cent of its lifetime with an eccentricity $e > 0.6$. These results imply that planetary orbits in binary stellar systems commonly experience periods of high eccentricity and dynamical chaos, and that such planets may occasionally collide with the primary star.

太阳系外行星

HD (仙后座)恒星：

离地球约20万光年



仙后座恒星示意图

The Astrophysical Journal, 578:L145-L148, 2002 October 20

Global Dynamics and Stability Limits for Planetary Systems around HD 12661, HD 38529, HD 37124, and HD 160691[1]

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Received 2002 July 19; accepted 2002 September 13; published 2002 September 24

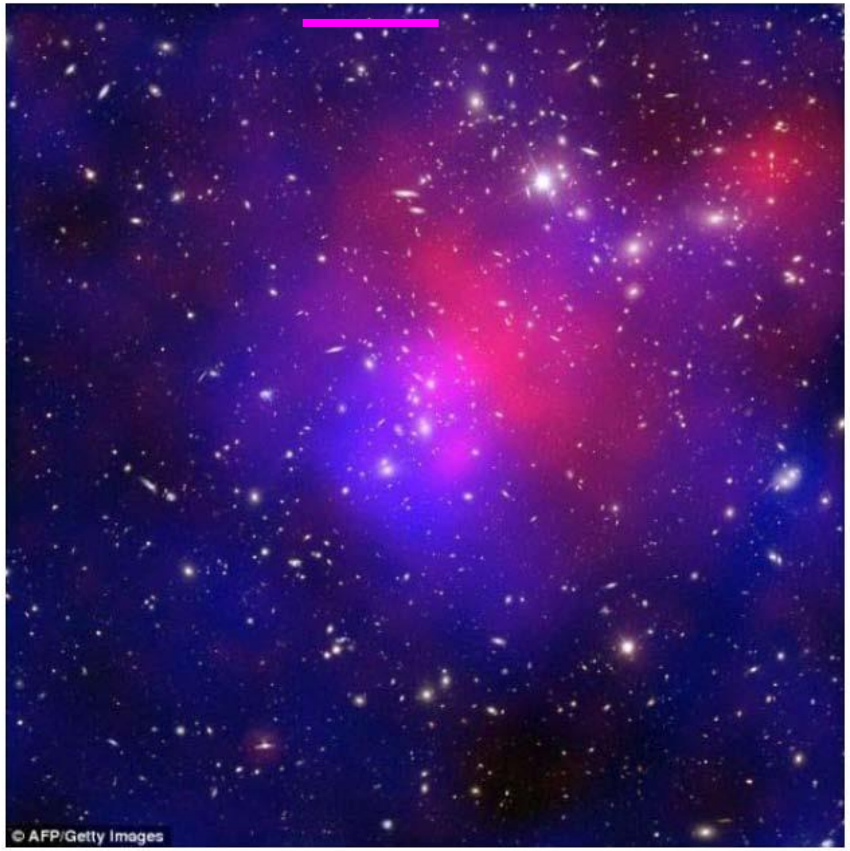
ABSTRACT

In order to distinguish between regular and chaotic planetary orbits, we apply a new technique, called the mean exponential growth factor of nearby orbits (MEGNO), in a wide neighborhood of orbital parameters determined using standard two-body Keplerian fits for the HD 12661, HD 38529, HD 37124, and HD 160691 planetary systems. We show that the currently announced orbital parameters place these systems in very different situations from the point of view of dynamical stability. While HD 38529 and HD 37124 are located within large stability zones in the phase space around their determined orbits, the preliminary orbits in HD 160691 are highly unstable. The orbital parameters of the HD 12661 planets are located in a border region between stable and unstable dynamical regimes, so while its currently determined orbital parameters produce stable regular orbits, a minor change within the margin of error of just one parameter may result in a chaotic dynamical system.

Subject headings: celestial mechanics; stellar dynamics; planetary systems; stars: individual (HD 12661, HD 37124, HD 38529, HD 160691)

[1] This work was carried out at Observatoire de Bordeaux (Université de Bordeaux I), France.
[2] Also a participating guest at Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, L-413, 7000 East Avenue, Livermore, CA 94550.

美科学家发现30亿光年外巨大星系群



这是阿贝尔-2744星系群的合成图像，由哈勃空间望远镜，钱德拉X射线望远镜，以及欧洲南方天文台甚大望远镜获取的图像叠加而成。图像中的粉色指代炙热的星系际气体，蓝色的则是暗物质。

http://news.sciencenet.cn/htmlnews/2011/6/248763.shtm?id=248763

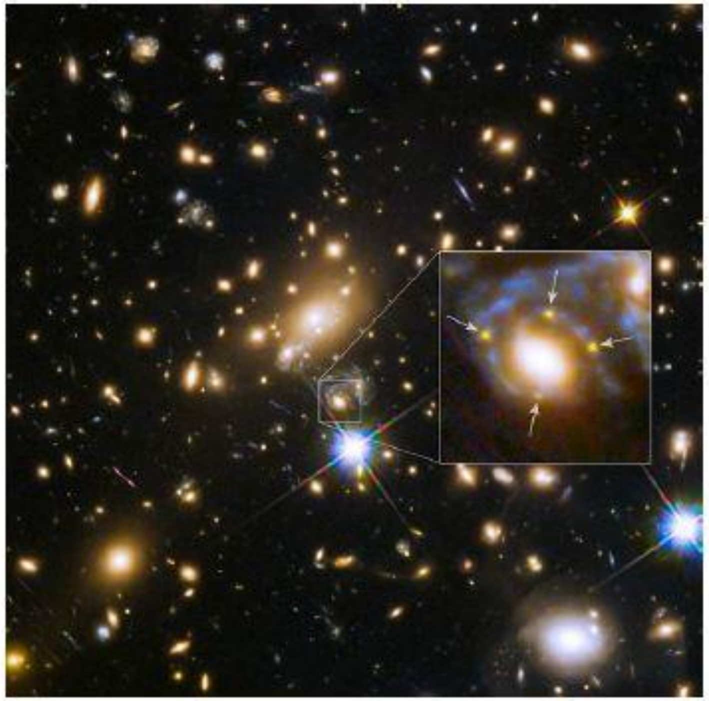
30 亿光年 ！

看来宇宙的本质就是混沌的，不是吗？

看见最遥远恒星，距地球超过 90 亿光年！

编辑：Steed　编译来源 Bad Astronomy，THE FARTHEST STAR

果壳网（guokr.com）2017-07-13



9 Billion Light Years
from Earth

霍金认为

黑洞的形成是一个经典意义下的混沌过程：

Information Preservation and Weather Forecasting for Black Holes*

S. W. Hawking[1]

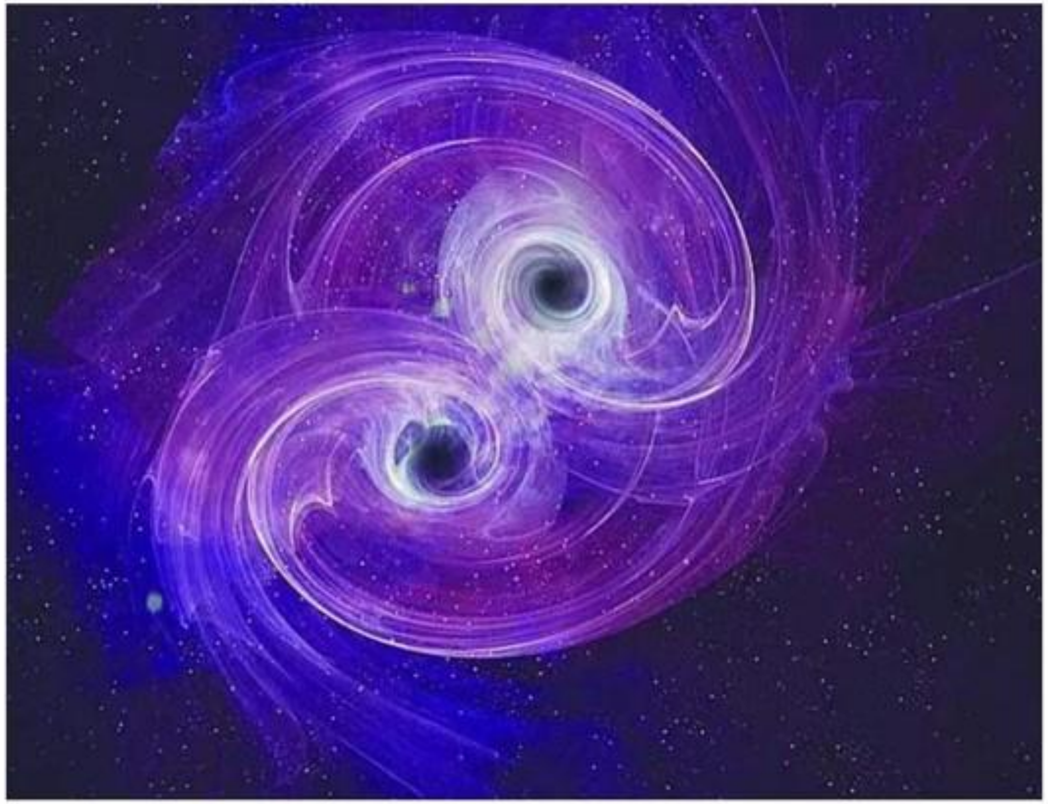
[1] *DAMTP, University of Cambridge, UK*

[hep-th] 22 Jan 2014

Abstract

It has been suggested [1] that the resolution of the information paradox for evaporating black holes is that the holes are surrounded by firewalls, bolts of outgoing radiation that would destroy any infalling observer. Such firewalls would break the CPT invariance of quantum gravity and seem to be ruled out on other grounds. A different resolution of the paradox is proposed, namely that gravitational collapse produces apparent horizons but no event horizons behind which information is lost. This proposal is supported by ADS-CFT and is the only resolution of the paradox compatible with CPT. The collapse to form a black hole will in general be chaotic and the dual CFT on the boundary of ADS will be turbulent. Thus, like weather forecasting on Earth, information will effectively be lost, although there would be no loss of unitarity.

9 引力波探测器发现迄今最强黑洞合并事件



黑洞碰撞概念图。图源/Science Photo Library

2019年5月21日，美国激光干涉引力波天文台LIGO 和意大利室女座干涉仪 Virgo 探测到两个黑洞的合并，将其命名为 GW190521

看来宇宙、自然和人类社会的本质就是混沌的，不是吗？

延申阅读：

洛伦兹：Lorenz

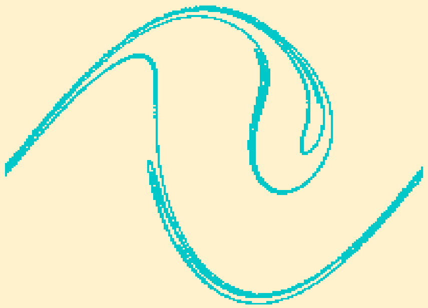
李天岩-约克-梅：Li-Yorke-May

玛丽-卡特赖特：Mary Cartwright

罗卡德：Rocard

阿诺德：Arnold

沙可夫斯基：Sharkovsky



总结与展望

- 混沌理论是复杂性科学的主要组成部分
- 混沌理论的发展走过了漫长的历史
- 混沌理论的研究向非双曲型系统深入
- 我们对量子混沌的演化机制所知甚少
- 混沌技术及其应用的发展方兴未艾
- 有兴趣、有条件、有机会的话，都来学一点“混沌”

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