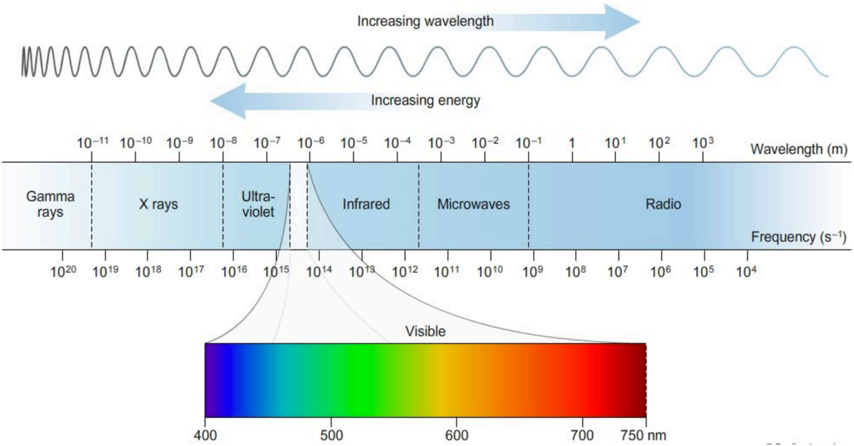
天体物理简介
— 优雅的孤勇者

魏星
北京师范大学天文系

清华大学求真书院
2023年2月24日

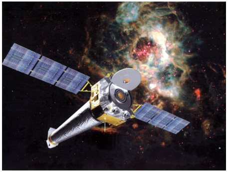
天文学既古老又年轻

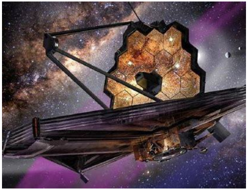


Increasing wavelength
Increasing energy
10−11 10−10 10−9 10−8 10−7 10−6 10−5 10−4 10−3 10−2 10−1 1 101 102 103
Wavelength (m)
Gamma rays
X rays
Ultra-violet
Infrared
Microwaves
Radio
Frequency (s−1)
1020 1019 1018 1017 1016 1015 1014 1013 1012 1011 1010 109 108 107 106 105 104
Visible
400
500
600
700
750 nm

地球大气只能透过可见光和射电波段

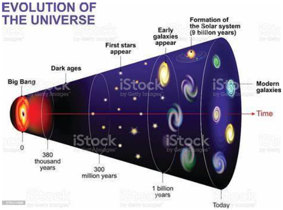


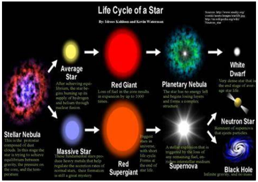



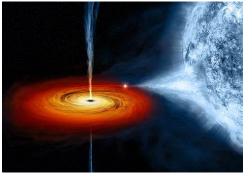


上排是地基望远镜：Keck(光学), 天眼(射电), ALMA(射电阵列)
下排是空间望远镜：钱德拉(X波段)，哈勃(紫外、可见光、近红外), 詹姆斯韦布(红外)

天体物理研究什么?







- 星系宇宙学：宇宙的起源和演化，宇宙大尺度结构、暗物质、暗能量
- 恒星行星：恒星、行星、行星系统的起源和演化
- 高能天体物理：致密天体（白矮星、中子星、黑洞）以及周围吸积盘释放的X射线、γ射线，并合释放的引力波

两暗一黑三起源：暗物质、暗能量、黑洞，宇宙起源、天体起源、生命起源

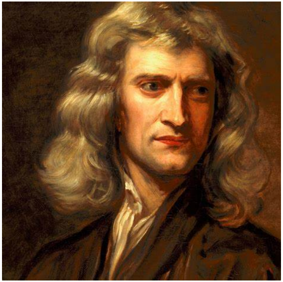
天文为什么迷人：因为她有过去、有现在、有未来，她是有故事的物理！

太阳中心密度多大？温度多高？将来会如何？这些我们都可以计算出来。我们只是地球上的生命，却可以通过数学和物理知道星星内部发生的事，是不是很有趣？只要你有想象力，又知道了基本的物理知识，就可以去当侦探，猜测这些星星以及整个宇宙以前发生过什么，正在发生什么，未来又会发生什么。创造知识，开拓人类知识的边界，在等着同学们！

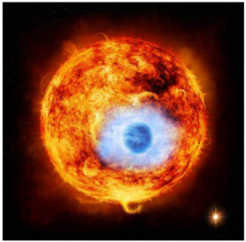
与天文有关的诺奖

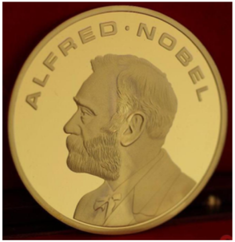
1936	宇宙线
1967	恒星能源
1970	宇宙磁流体
1974	射电天文学、脉冲星
1978	宇宙微波背景辐射
1983	恒星结构演化、宇宙元素合成
1993	脉冲双星
2002	宇宙中微子、X射线天文学
2006	宇宙微波背景辐射的黑体形式和各向异性
2011	宇宙加速膨胀
2017	引力波
2019	系外行星、宇宙学
2020	黑洞
2021	行星大气

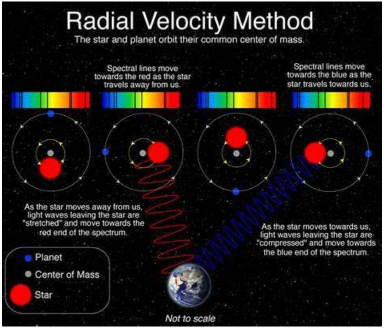
进入21世纪后，得益于望远镜和探测设备的快速发展，诺奖青睐天文学，鼓励人类揭开星空的奥秘，走出地球。

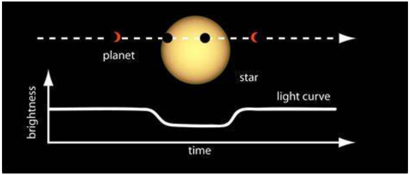
 

牛顿的万有引力和爱因斯坦的广义相对论都是关于天上的事，科学的下一次巨大变革是否依然来自天文?





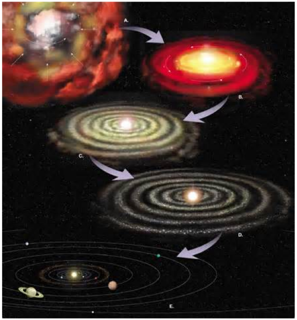




视向速度法：多普勒效应　　　掩星法

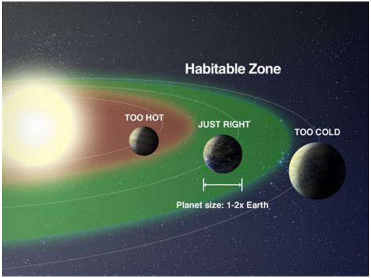
研究系外行星的意义：

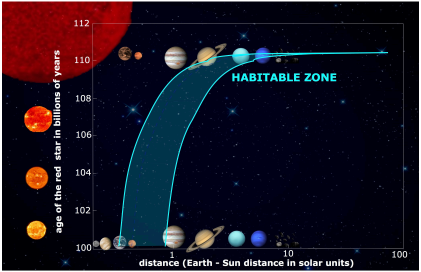
- 开拓人类认知的边界
- 为人类寻找另一个家园
- 理解我们太阳系的形成和演化



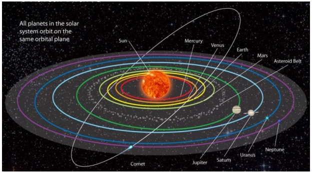
哲学家康德：星云假说
数学家拉普拉斯：列方程算

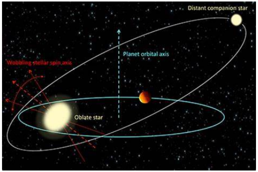
宜居性


Habitable Zone
TOO HOT
JUST RIGHT
TOO COLD
Planet size: 1-2x Earth

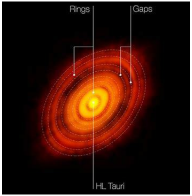

HABITABLE ZONE
age of the red star in billions of years
112
110
108
106
104
102
100
1
10
100
distance (Earth - Sun distance in solar units)

行星轨道动力学



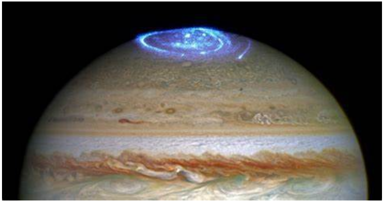


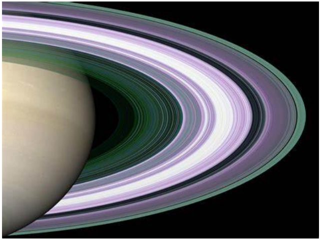
行星形成



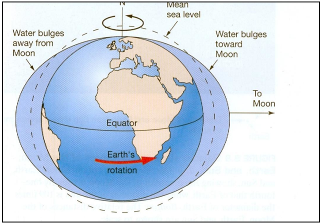
(热木星的形成：盘内迁移、高偏心率迁移)

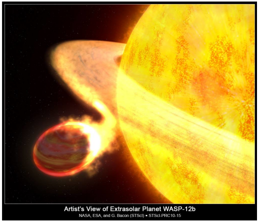
行星大气、行星极光、行星环



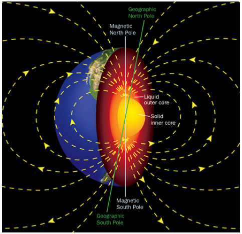


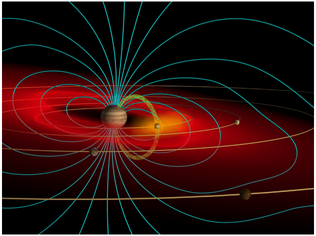
行星潮汐


N
Mean
sea level
Water bulges
away from
Moon
Water bulges
toward
Moon
To
Moon
Equator
Earth's
rotation


Artist's View of Extrasolar Planet WASP-12b
NASA, ESA, and G. Bacon (STScI) • STScI-PRC10-15

行星磁场


Geographic
North Pole
Magnetic
North Pole
Liquid
outer core
Solid
inner core
Magnetic
South Pole
Geographic
South Pole



- 观测：各个波段，包括X射线、紫外、光学、红外、射电
- 理论：轨道动力学、流体力学、电磁学(辐射)

$$\boldsymbol{F} = m\boldsymbol{a}, \quad \rho\frac{d\boldsymbol{v}}{dt} = -\nabla P + \boldsymbol{f},$$
$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}, \quad \nabla \times \boldsymbol{B} = \mu\left(\boldsymbol{J} + \epsilon\frac{\partial \boldsymbol{E}}{\partial t}\right).$$

孤勇者的故事

1930年，一位20岁的青年离开印度坐船去英国剑桥读博士，在船上做了一个计算，将狭义相对论应用到了恒星的结构，结果发现：恒星的归宿可能不只是白矮星，如果白矮星质量超过1.44倍太阳质量，则会继续坍缩，那么...

这位青年叫钱德拉塞卡，他的叔叔是物理诺奖得主拉曼(拉曼散射)，他的偶像是天才数学家拉玛努金。

$$\nabla p = \rho \mathbf{g} \Longrightarrow p/R \simeq (M/R^3)(GM/R^2) \simeq GM^2/R^5$$

$$p = K\rho^{1+1/n} \simeq K(M/R^3)^{1+1/n}$$

$$\Longrightarrow GM^{1-1/n} \simeq KR^{1-3/n}$$

非相对论: $n = 3/2$, 相对论: $n = 3$

非相对论: $R \simeq (K/G)M^{-1/3}$, 相对论: $M \simeq (K/G)^{3/2}$

相对论情形下，质量有上限

物理解释: 电子运动速度有上限(光速)，压力(电子简并压)就有上限，压力抗不住自引力，恒星就会继续坍缩

意义: 星星质量有上限

他在剑桥继续这方面的工作，1935年他在皇家天文学会的年会上做报告。报告做完，剑桥教授、天文学会主席爱丁顿宣布：“十分古怪的结论，一定有自然法则阻止恒星这种荒谬的行为”。他找到不少物理学家求助，尽管大家都知道他是对的，但都不愿意得罪爱丁顿。于是，他选择**不争论**，去了美国芝加哥大学。

他把结果发表在 Astrophysical Journal，写了一本书，就不再关心这个问题，继续其它领域的研究。每十年换一个**冷门**领域，每个领域都做到顶尖水平，然后写一本书。"钱德拉塞卡风格。"

“每十年投身一个新领域，可以**保持谦虚**，不可能与年轻人闹矛盾，因为他们比你在这个领域干得时间更长”。

- 1939 恒星结构: 钱德拉塞卡极限
- 1942 恒星动力学: 动力学摩擦
- 1950 辐射转移: 恒星大气和负氢离子
- 1961 流体和磁流体稳定性: 吸积盘的磁旋转失稳
- 1969 椭球体的稳定性: 天体形状和稳定性
- 1983 黑洞数学理论: 回到了最初的研究
- 1995 重写牛顿的《原理》: 为当代人翻译《原理》

Astrophysical Journal 主编，20年将其从芝加哥大学校报变成天文主流期刊。每周工作7天，每天工作12小时，用10年左右的时间，搞明白宇宙的某个方面。“钱德拉塞卡没有极限。”

53年后，他73岁时因为20岁的那个发现，获得了1983年诺贝尔奖。点评："埋头写下一篇论文，抬起头时双鬓已白。"科研不是百米赛跑，而是马拉松，贵在<u>坚持</u>，抵住困难和诱惑。

问：你最开始时为啥做科研？答：希望借助于献身科学取得成就出名。点评：年轻时想出名无可厚非，经过打击后对名利慢慢淡泊，更享受科学研究本身。

问：你在美国这些年咋样？答：受到过一些种族歧视和不公正待遇，但后知后觉。点评：迟钝一些可能有好处，可以专心学问，否则太分心，做不好科研。

问：你对爱丁顿这事咋看？答：如果他当时承认我的研究，我就不会有后面那么多研究成果。点评：事情多从另一个角度看看。

问：你对爱丁顿这人咋看？答：老派英国绅士，高傲到以为自己可以制定自然法则，但他确实是一名出色的天文学家，后来与他和解了。点评：对自然保持谦卑，对人保持宽容。

帕克的故事

彗星的气体尾总是背向太阳，比尔曼提出猜想：太阳可能发射带电粒子。芝加哥大学的权威辛普森教授让年轻老师帕克去计算一下比尔曼的猜想，否定这个猜想。结果出人意料，帕克的计算证实了比尔曼的猜想有道理，太阳的引力束缚不住粒子向外运动。帕克的论文投出去却一直被据稿，1958年，他投到ApJ，先是被两个审稿人据稿，接着钱德拉塞卡亲自审稿。“虽然我也不信你说的，但计算没错，准许发表”。仅仅一年后的1959年，苏联的人造卫星升空，发现了帕克的太阳风。

钱德拉塞卡自己年轻时遭受过权威打压，这可能也是他同意帕克论文发表的一个原因。

ON STARS, THEIR EVOLUTION AND THEIR STABILITY

Nobel lecture, 8 December, 1983

by

SUBRAHMANYAN CHANDRASEKHAR

The University of Chicago, Chicago, Illinois 60637, USA

1. *Introduction*

When we think of atoms, we have a clear picture in our minds: a central nucleus and a swarm of electrons surrounding it. We conceive them as small objects of sizes measured in Angstroms (~10^{-8} cm); and we know that some hundred different species of them exist. This picture is, of course, quantified and made precise in modern quantum theory. And the success of the entire theory may be traced to two basic facts: *first*, the Bohr radius of the ground state of the hydrogen atom, namely,

$$\frac{h^2}{4\pi^2 me^2} \sim 0.5\times 10^{-8}\ \text{cm}, \tag{1}$$

where h is Planck's constant, m is the mass of the electron and e is its charge, provides a correct measure of atomic dimensions; and *second*, the reciprocal of *Sommerfeld's fine-structure constant*,

$$\frac{hc}{2\pi e^2} \sim 137, \tag{2}$$

gives the maximum positive charge of the central nucleus that will allow a stable electron-orbit around it. This maximum charge for the central nucleus arises from the effects of special relativity on the motions of the orbiting electrons.

We now ask: can we understand the basic facts concerning stars as simply as we understand atoms in terms of the two combinations of natural constants (1) and (2). In this lecture, I shall attempt to show that in a limited sense we can.

The most important fact concerning a star is its mass. It is measured in units of the mass of the sun, $\odot$, which is 2 x 10^{33} gm: stars with masses very much less than, or very much more than, the mass of the sun are relatively infrequent. The current theories of stellar structure and stellar evolution derive their successes largely from the fact that the following combination of the dimensions of a mass provides a correct measure of stellar masses:

$$\left(\frac{hc}{G}\right)^{3/2} \frac{1}{H^2} \simeq 29.2\,\odot, \tag{3}$$

where G is the constant of gravitation and H is the mass of the hydrogen atom. In the first half of the lecture, I shall essentially be concerned with the question: how does this come about?

Expansions including terms of $O(r^{l+2})$ can readily be found by standard procedures. In particular, by assuming an expansion of the form

$$(X, \mathscr{G}, N, L) = (X_0, \mathscr{G}_0, N_0, L_0)\, r^l + (X_2, \mathscr{G}_2, N_2, L_2)\, r^{l+2} + O(r^{l+4}) \tag{82}$$

we find

$$\left.\begin{aligned}
&(l+2)(l+3)X_2 + n(N_2+L_2) + l(a-b)X_0 + nb(N_0+L_0) + \sigma_0^2 X_0 = 0,\\
&[(l+2)(a-b)+\sigma_0^2]X_2 - (l+4)\mathscr{G}_2 + n(a+b)N_2 - n(a-b)L_2\\
&\qquad + n(a_2+b_2)N_0 - n(a_2-b_2)L_0 + l(a_2-b_2^{(2)})X_0 + \sigma_0^2(b-a)X_0 = 0,\\
&-\mathscr{G}_2 + [(l+1)a + \tfrac{1}{2}\sigma_0^2]N_2 + \tfrac{1}{2}\sigma_0^2 L_2 + \left[(l+2)(a-b) + \frac{(l+1)^2}{2n}\sigma_0^2\right]X_2\\
&\qquad + [a_2 l + a^2 + b_2 - b(\epsilon_0+p_0) + (\epsilon_2+p_2) + \tfrac{1}{2}\sigma_0^2(b-a)]N_0\\
&\qquad + [\tfrac{1}{2}\sigma_0^2(b-a) - a^2]L_0 + \left[l(a_2-b_2) + \frac{\sigma_0^2}{2n}(b-a)(l^2+2l-1)\right]X_0 + \left(\frac{\sigma_0^2}{2n} - b\right)\mathscr{G}_0 = 0,\\
&(l+3)\left[N_2 + L_2 + \frac{l(l+1)}{n}X_2\right] - a\left\{Q_0 N_0 - (Q_0-2)L_0 + \left[2 + (l+1)\frac{Q_0+1}{n}\right]X_0\right\} + \frac{2}{n}\mathscr{G}_0 = 0.
\end{aligned}\right\} \tag{83}$$

where we may insert for $(X_0, \mathscr{G}_0, N_0, L_0)$ either of the two solutions (80) or (81).

7. The interior solution

A solution that describes the interior of a star must satisfy certain requirements at the centre, $(r=0)$, and at the boundary, $(r=r_1)$, where the pressure p of the static star vanishes.

At the centre the conditions are that $\delta\epsilon$ and δp (i.e. E and Π) both vanish. (A somewhat milder requirement may suffice: but the stronger conditions that $E = \Pi = 0$ and singularity free, are certainly sufficient.) By equations (35) and (37), the conditions are met by the requirement that W and N vanish at $r=0$. Of the solutions allowed by the indicial equation (78), only the two linearly independent solutions with the r^l-behaviour at the origin are compatible with the physical requirements. These solutions are explicitly determined by the expansions specified in equations (80)–(83). (It may be noted here that the r^l-behaviour of the functions N, L, X, and W assures the required flatness of the space-time at the origin.)

At the boundary, $r=r_1$, of the star two conditions must be met: Π must vanish and we must also ensure that the space-time is continuous with the vacuum that prevails outside the star. (Strictly we need only require that Π vanishes on the displaced moving boundary of the oscillating star. This distinction between the static boundary and the moving boundary is relevant only if $\epsilon \neq 0$ on $r=r_1$. Allowance for this contingency is readily made: but we shall not digress now to consider this eventuality.) The vanishing of Π clearly requires (under the circumstances envisaged, namely that ϵ and p vanish on $r=r_1$)

$$W = -(T - V + L) = 0 \quad \text{at} \quad r = r_1 \tag{84}$$

and this is also one of the conditions that the metric perturbations are required to satisfy (cf. *M.T.*, p. 147, eqn (43)) in order to match continuously with the exterior metric perturbations – we consider the remaining conditions in §8 below.

The condition (84) on W follows from either of the equations (27) and (37). More stringent conditions on W follow from equations (26) and (45). The former equation,

书和论文非常严谨，方程喜欢写分量形式。左图：诺奖演讲稿，是一篇60个方程、7张图、2个表格、22篇参考文献组成的论文。右图：80岁时的论文，还在做着繁琐艰苦的计算。“科学的发展不是靠这个或那个发现，也不是靠撰写或发表一篇论文，而是靠热忱的研究和大量的工作。”

星星的质量确定了，其命运基本就确定了，而人比星星幸运。

“命运对于我们并无所谓利害，它只供给我们利害的原料和种子，任那比它强的灵魂随时变换运用，因为灵魂才是自己的幸与不幸的唯一主宰。”— 蒙田

The simple is the seal of the true

Beauty is the splendour of truth

简单是真理的标记

美是真理的光辉

求真 $\Longleftrightarrow$ 简单、美