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The Living Record of Science

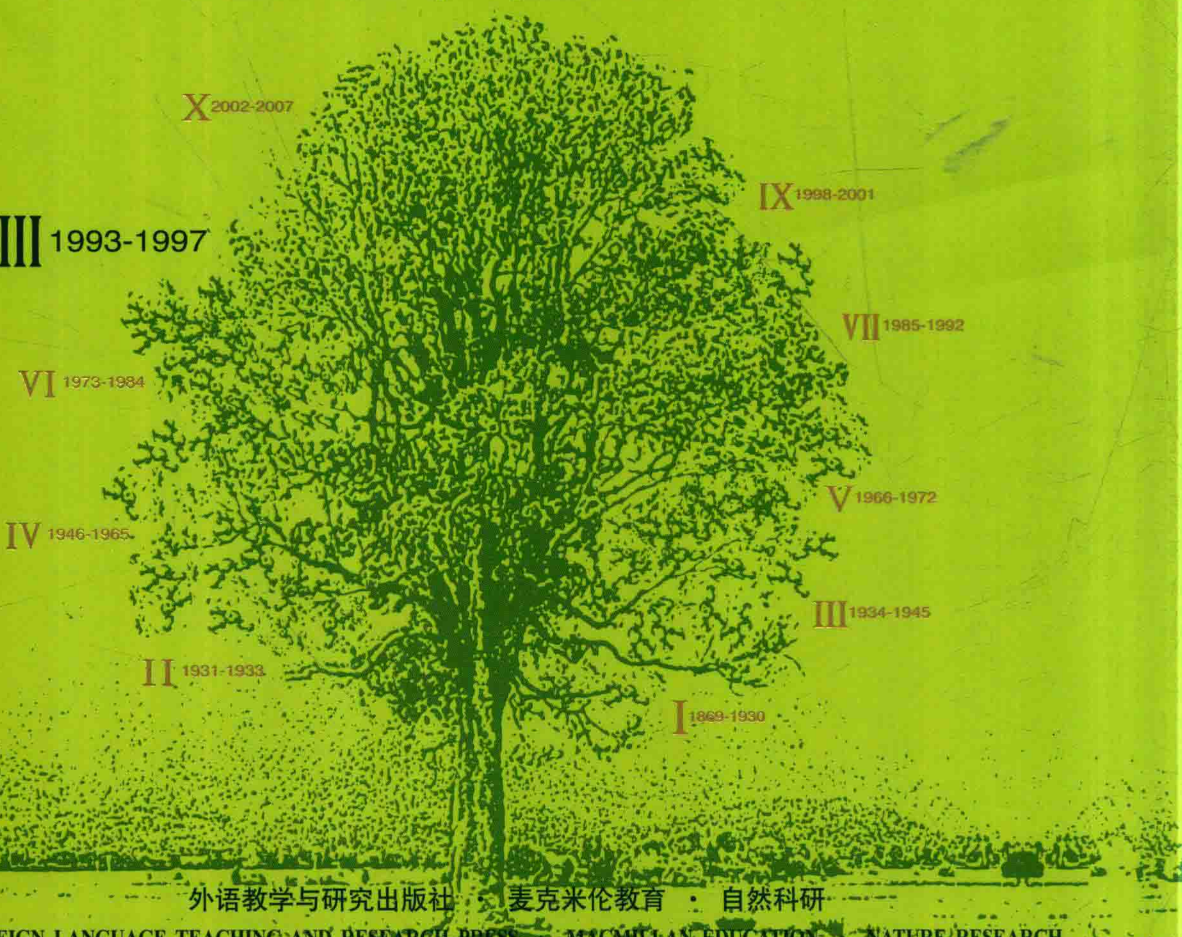
《自然》百年科学经典

英汉对照版（平装本）

第八卷（下）

总顾问：李政道（Tsung-Dao Lee）

英方主编：Sir John Maddox
Sir Philip Campbell
中方主编：路甬祥



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(1993-1997)

Distance to the Virgo Cluster Galaxy M100 from Hubble Space Telescope Observations of Cepheids

W. L. Freedman *et al.*

Editor's Note

In astronomy it is essential to know the distance to any object, because only then can the observed brightness at any wavelength be converted to the true luminosity. Variable stars called Cepheids are central to working out this "distance ladder", because their luminosity is closely related to their period and can thus be determined independently. Here Wendy Freedman and colleagues use the Hubble Space Telescope to determine the Cepheid distance to the galaxy M100, and thereby determine an accurate value for the Hubble constant, which measures the expansion rate of the Universe. This was one of the key design goals for the HST. The initial value of ~80 km s^{-1} Mpc^{-1} was refined over the following decade.

Accurate distances to galaxies are critical for determining the present expansion rate of the Universe or Hubble constant (H_0). An important step in resolving the current uncertainty in H_0 is the measurement of the distance to the Virgo cluster of galaxies. New observations using the Hubble Space Telescope yield a distance of 17.1 ± 1.8 Mpc to the Virgo cluster galaxy M100. This distance leads to a value of $H_0 = 80 \pm 17$ km s^{-1} Mpc^{-1}. A comparable value of H_0 is also derived from the Coma cluster using independent estimates of its distance ratio relative to the Virgo cluster.

WITHIN the framework of general relativity, the evolution of the Universe can be specified by the Friedmann equation which relates the expansion rate H, to the mean mass density ρ, the curvature k, and a possible additional term, called the cosmological constant Λ (identified with the gravitational effects of the vacuum energy density). In a uniform and isotropic Universe the relative expansion velocity v is proportional to the relative distance r such that $v = H \times r$. Thus a determination of the present-day value of the Hubble constant H_0 determines both the expansion timescale and the size scale of the Universe. The Hubble constant also provides constraints on the density of baryons produced in the Big Bang, the amount of dark matter, and how structure formed in the early Universe[1,2].

Despite 65 years of study, the value of the Hubble constant has remained in dispute. Although the measurement of relative velocities of galaxies is straightforward, the measurement of accurate distances has always been more difficult. For distances out to ~5 Mpc, there is now general agreement[3,4] to a level of better than $\sim \pm 10\%$. However, for

由哈勃空间望远镜观测造父变星到室女星系团成员星系 M100 的距离

弗里德曼等

编者按

在天文学中，知道任意天体的距离是重要的，因为只有这样才能将任意波长处观测到的亮度转换为真实的光度。被称作造父变星的变星对得到“距离阶梯”尤为重要，因为它们的光度和它们的光变周期紧密相关，因而它们的光度可以独立地测定。在这篇文章中，温迪·弗里德曼和他的同事们利用哈勃空间望远镜测定到 M100 星系的造父距离，并从而测定哈勃常数（衡量宇宙膨胀率的参数）的精确值。确定哈勃常数是哈勃空间望远镜的主要设计目标之一。它最初的值 ~80 km · s^{-1} · Mpc^{-1} 在之后的几十年中得到了修正。

测定到星系的精确距离对于测定目前的宇宙膨胀率或哈勃常数 (H_0) 是至关重要的。解决目前 H_0 不确定性的重要一步是测量到室女星系团的距离。使用哈勃空间望远镜新的观测得到的到室女星系团成员星系 M100 的距离为 17.1 ± 1.8 Mpc。由这一距离得到 H_0 = 80 ± 17 km · s^{-1} · Mpc^{-1}。利用后发星系团相对室女星系团距离比进行独立的测定，也得到了相近的 H_0 值。

在广义相对论的框架内，宇宙的演化可以用弗里德曼方程描述，这一方程将膨胀率 H 与平均质量密度 ρ、曲率 k 以及一个称作宇宙学常数 Λ（等同于真空能量密度的引力作用）的可能的附加项联系起来。在一个均匀且各向同性的宇宙中，相对膨胀速度 v 正比于相对距离 r，即 $v = H \times r$。因此，测定哈勃常数的当前值 H_0 就同时得到了宇宙的膨胀时标和尺度。哈勃常数也对大爆炸时期产生的重子物质密度、暗物质的数量以及宇宙早期结构的形成都具有约束作用[1,2]。

尽管经过了 65 年的研究，但是哈勃常数的值仍然存在争议。尽管测量星系间的相对速度是直接的，然而测量星系间的精确距离却困难得多。目前普遍认为，对于大约 5 Mpc 的距离的测定，测量的精度高于 ±10%[3,4]。然而，对于像到室女星系团这么遥远的目标的距离，测量结果存在很大的分歧[5,6]，其测量值大约在 15 Mpc 到

distances as great as the Virgo cluster there is a significant discrepancy[5,6], with quoted values ranging from about 15 to 24 Mpc. Not only is there a range of published distances, but there is a tendency for the values to cluster at the extremes, giving rise to the so-called "short" and "long" distance scales.

The most accurate means of measuring the distances to galaxies has proved to be the application of a relationship between the period and the luminosity for a class of supergiant variable stars known as classical Cepheids. In fact, Cepheids were used by Edwin Hubble to demonstrate the extragalactic nature of the spiral nebulae[7,8]. They are relatively young, massive stars with luminosities ~1,000 to 100,000 times brighter than the Sun ($-2 < M_V < -7$ mag). They are well calibrated; they are easy to identify in external galaxies because of their variability and brightness; and they have measured dispersions in the *V*- and *I*-band period–luminosity (*P–L*) relationships amounting to only ± 0.25 and ± 0.20 mag, respectively[3]. In addition, the underlying physical basis for the Cepheid *P–L* relation is well understood.

Unfortunately, Cepheids are not luminous enough to be observed out to distances where galaxies are participating in the free expansion of the Universe. The motions of individual galaxies can be perturbed by interactions with nearby neighbouring galaxies; in addition, galaxies can participate in large-scale flows[9,10]. Hence, to measure the pure Hubble flow, other (secondary) distance techniques must be used to extend the extragalactic distance scale beyond the observable range of the Cepheids, to recession velocities of a few thousand km s^{-1} where peculiar velocities (which can amount to several hundred km s^{-1}) are small in comparison to the expansion velocity.

The Virgo cluster of galaxies is close enough to be studied in detail; and yet it is far enough away that it is of cosmological interest. It is rich in both spiral and elliptical galaxies and therefore it has played a critical role in the extragalactic distance scale and determination of the Hubble constant. Thus obtaining a Cepheid distance to the Virgo cluster represents a crucial step in resolving the current uncertainty in H_0 and resolving the dichotomy in distance estimates. A variety of other techniques for measuring distances have been applied to the Virgo cluster; hence, an accurate direct measure of the distance to this cluster can be used to calibrate (or set the zero point for) other secondary distance indicators.

The Key Project

The goal of the Hubble Space Telescope Key Project on the extragalactic distance scale is to provide a measure of the Hubble constant accurate to 10%. This aim is non-trivial given that the history of previous attempts to measure the extragalactic distance scale is replete with examples where large systematic errors were eventually revealed. Hence, the determination of accurate distances requires careful attention to eliminating potential sources of systematic error.

24 Mpc 之间。已经发表的距离不仅范围很大，而且到星系团的距离还存在着两种极端趋势，即所谓“短”的和“长”的距离尺度。

已经证实的测量星系团距离最精确的方法是应用被称作经典造父变星的一类超巨星变星的周光关系。事实上，造父变星曾被埃德温·哈勃用来解释旋涡星云位于银河系之外[7,8]。它们是相对年轻的大质量恒星，其光度是太阳的约 1,000 倍到 10,000 倍（-2 mag < M_V < -7 mag）。它们已经被很好地定标过；由于其光变和亮度，它们很容易在河外星系中被识别出来；它们在 V 波段与 I 波段的周光关系中测量出的弥散度分别只有 ±0.25 mag 和 ±0.20 mag[3]。另外，我们对于造父变星周光关系的物理机制也已经有了较好的了解。

遗憾的是，造父变星由于亮度不够，在宇宙自由膨胀的星系中，还不能被观测到。个别星系的运动可能在与邻近星系的相互作用中受到干扰；另外，星系可能参与大尺度的流动[9,10]。因此，为了测量纯粹的哈勃流，必须使用其他的（次级的）距离测量技术，以便将河外星系的距离尺度扩展到造父变星的可观测范围之外，在这一区域退行速度为每秒几千千米，而本动速度（大小只有每秒几百千米）与宇宙的膨胀速度相比则很小。

室女星系团距离我们足够近，可以详细地加以研究；而且从宇宙学研究的角度来看，它也足够远。该星系团富含旋涡星系和椭圆星系，这使得它在河外星系的距离尺度和哈勃常数测定上都扮演着至关重要的角色。因此，获得室女星系团的造父距离，对于解决当前 H_0 测定的不确定性以及距离估计上的分歧，都是关键的一步。鉴于各种测定距离的其他方法都已经用到了室女星系团；因此，精确地直接测量到这个星系团的距离可以用来定标（或者设置零点）所有其他的次级示距天体。

关键项目

哈勃空间望远镜关于河外距离尺度的关键项目主要目标是将哈勃常数的测量精度提高到 10%。考虑到之前河外距离尺度测量的历史中充斥的许多事例（最终都被证实存在着很大的系统误差），就会发现这一目标是意义非凡的。因此，精确距离的测量要求仔细地去消除潜在的各种系统误差。

The strategy adopted by the Key Project team on the extragalactic distance scale is threefold. The first goal is to discover Cepheids, and thereby measure accurate primary distances to spiral galaxies located in the field and in small groups that are suitable for the calibration of several independent secondary methods. (These secondary methods include: the Tully–Fisher relationship[11,12], the surface-brightness fluctuation method[13], the planetary nebula luminosity function[14], the expanding photosphere method applied to type II supernovae[15,16], and the measurement of the luminosities of type Ia supernovae[6,17-19].) The second objective is to provide a check on potential systematic errors in the Cepheid distance scale through independent distance estimates to the nearby galaxies, M31, M33 and the Large Magellanic Cloud (LMC) and, in addition, to undertake an empirical test of the sensitivity of the zero point of the Cepheid *P–L* relationship to heavy-element abundances. The third and most challenging observational goal is to make Cepheid measurements of distances to three spiral galaxies in the Virgo cluster and two members of the Fornax cluster.

The Distance to M100

Our first observations aimed at finding Cepheids in a Virgo cluster galaxy were made in a two-month period beginning in April 1994 with a sequence of 12 1-hour *V*-band exposures of a field ~2 arcmin east of the nucleus of M100. The observing strategy was designed to provide well-sampled light curves for Cepheids having periods ranging from 10 to 60 days. In addition, *I*-band exposures were taken back-to-back with 4 of the *V* observations. We present here sample light curves for the Cepheids discovered, their *V*-band and *I*-band *P–L* relationships, and a preliminary estimate of the distance to M100. Details of the data reduction and analysis, tabulation of the photometry, and identification of the variables will be presented elsewhere (L.F. *et al.*, manuscript in preparation; R.H. *et al.*, manuscript in preparation). Three independent calibrations of the photometric zero points were made; the final resulting uncertainties in the *V* and *I* zero points amount to ± 0.05 and ± 0.04 mag, respectively. A description of the sampling strategy used for the optimal discovery of variables, and of the method used for identification of variables, determination of mean magnitudes, reddening, and distance have been published elsewhere[20].

V-band light curves for twelve M100 Cepheids are illustrated in Fig. 1. The total sample of Cepheids has a range of periods from 20 to 65 days, and mean *V* magnitudes ranging from 25.0 to 26.5 mag. It is evident from the small scatter in the light curves that the quality of the photometry being obtained by the Hubble Space Telescope (HST) is excellent. Internal estimates of the random errors for single data points are found to be ± 0.14 mag at $V \approx 25$ mag and ± 0.17 mag at $V \approx 26$ mag. The errors in the mean magnitudes for the 12 epochs amount to ± 0.04 and ± 0.05 mag at these same magnitude levels.

关键项目的研究小组在河外距离尺度问题上采取的策略包括三个目标。第一个目标是发现造父变星，在此基础上测量到位于星场中以及位于小星系群内的旋涡星系的精确初级距离，这一结果适合于定标几种相互独立的次级距离测量方法。(这些次级距离测量方法包括：塔利－费希尔关系[11,12]、面亮度起伏方法[13]、行星状星云光度函数法[14]、在Ⅱ型超新星上使用的膨胀光球法[15,16]，以及 Ia 型超新星光度测量法[6,17-19]。) 第二个目标是通过邻近星系 M31、M33 以及大麦哲伦云（LMC）距离的独立测算检验造父距离的潜在系统误差。此外，还可以经验性地检验造父变星周光关系的零点对重元素丰度的敏感性。第三个也是最具挑战性的观测目标是利用造父变星测量出室女星系团内的三个旋涡星系以及天炉星系团内两个成员星系的距离。

到 M100 的距离

我们的第一个观测目标是寻找室女星系团内的造父变星，通过对 M100 核心区域偏东约 2 arcmin 的视场进行 12 幅为一序列，每幅曝光时间为 1 小时的 V 波段测光，这一观测过程从 1994 年 4 月开始延续了两个月。采取这样的观测策略是为了给光变周期处于 10 天到 60 天的造父变星提供较好的光变曲线采样点。另外，紧接着 4 组 V 波段观测，我们进行了 I 波段的观测。这里，我们给出了所发现的造父变星的样本光变曲线，它们在 V 波段和 I 波段的周光关系，以及初步估计的到 M100 的距离。数据处理与分析的细节，测光列表以及变星的认证将另文发表（温迪·弗里德曼等，稿件准备中；罗伯特·希尔等，稿件准备中）。我们使用了三种独立的测光零点定标；V 波段和 I 波段零点最终结果的不确定性分别为 ±0.05 mag 和 ±0.04 mag。用于最优地发现变星的采样策略，以及认证变星、确定平均星等、红化值以及测量距离的方法都已经在其他地方发表[20]。

在图 1 中展示了 M100 内 12 颗造父变星在 V 波段的光变曲线。所有造父变星样本的光变周期从 20 天到 65 天，平均 V 星等的范围从 25.0 mag 到 26.5 mag。由光变曲线很小的散射证明哈勃空间望远镜的测光质量是非常好的。单一数据点的随机误差的自身估计在 $V \approx 25$ mag 时为 ±0.14 mag，在 $V \approx 26$ mag 时为 ±0.17 mag。对于 12 次观测得到的平均星等的误差在相同星等条件下分别为 ±0.04 mag 以及 ±0.05 mag。