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The Living Record of Science

《自然》百年科学经典

（英汉对照版）

第九卷

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

IX 1998-2001

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Discovery of a Supernova Explosion at Half the Age of the Universe

S. Perlmutter *et al.*

Editor's Note

In the early 1990s it became possible to use type Ia supernovae as "standard candles" to determine astronomical distances. Using this approach, Saul Perlmutter and coworkers here report a supernova at a redshift of 0.83 that is fainter than expected. Although they initially interpreted the faintness as evidence that the universe has a lower average density than was thought, it was soon realized that the best explanation is that the universe is expanding at an accelerating rate. This is now the accepted view, although the reason is unclear and represents one of the central puzzles in contemporary cosmology. One interpretation is that the universe is pervaded by "dark energy" that creates a repulsive force, counteracting gravitational attraction.

The ultimate fate of the Universe, infinite expansion or a big crunch, can be determined by using the redshifts and distances of very distant supernovae to monitor changes in the expansion rate. We can now find[1] large numbers of these distant supernovae, and measure their redshifts and apparent brightnesses; moreover, recent studies of nearby type Ia supernovae have shown how to determine their intrinsic luminosities[2-4]—and therefore with their apparent brightnesses obtain their distances. The > 50 distant supernovae discovered so far provide a record of changes in the expansion rate over the past several billion years[5-7]. However, it is necessary to extend this expansion history still farther away (hence further back in time) in order to begin to distinguish the causes of the expansion-rate changes—such as the slowing caused by the gravitational attraction of the Universe's mass density, and the possibly counteracting effect of the cosmological constant[8]. Here we report the most distant spectroscopically confirmed supernova. Spectra and photometry from the largest telescopes on the ground and in space show that this ancient supernova is strikingly similar to nearby, recent type Ia supernovae. When combined with previous measurements of nearer supernovae[2,5], these new measurements suggest that we may live in a low-mass-density universe.

SN1997ap was discovered by the Supernova Cosmology Project collaboration on 5 March 1997 UT, during a two-night search at the Cerro Tololo Interamerican Observatory (CTIO) 4-m telescope that yielded 16 new supernovae. The search technique finds such sets of high-redshift supernovae on the rising part of their light curves and guarantees the date of discovery, thus allowing follow-up photometry and spectroscopy of the transient supernovae to be scheduled[1]. The supernova light curves were followed

在宇宙年龄一半处发现的超新星爆发

珀尔马特等

编者按

在20世纪90年代的早期，使用Ia型超新星作为“标准烛光”测定天文学距离已成为可能。使用这种方法，索尔·珀尔马特以及他的合作者们在这里报道了在红移0.83处比预期的暗淡的一颗超新星。尽管他们最初把这颗超新星的暗淡解释为宇宙的平均密度比普遍认为的要低的证据，但是很快他们意识到最好的解释是宇宙的膨胀在加速。现在这个观点已经被普遍认可，尽管原因尚不知晓，这也是当代宇宙学最主要的难题之一。一种解释是宇宙中充斥着暗能量，产生排斥力，与引力相抗衡。

宇宙的命运最终是无限膨胀还是大挤压，可以通过测量遥远超新星的红移和距离，进而监测宇宙膨胀速率的变化来确定。我们现在发现了大量遥远的超新星[1]，并且测定了它们的红移和视亮度；而对较近Ia型超新星的研究已经找到了测定本征光度[2-4]的方法，通过它们的视亮度就能得到距离。至今已发现的50多个远距离Ia型超新星记录了过去几十亿年间宇宙膨胀速率的变化[5-7]。不过我们还需要进一步追溯更远(即时间上更早)的宇宙膨胀历史，从而找出宇宙膨胀速率变化的原因——是在宇宙质量密度的引力影响下变慢，或是由宇宙学常数的反作用而加速[8]。我们在此报道一颗已获光谱确认的最遥远的超新星。来自地面和空间中最大望远镜的光谱和测光数据表明这颗古老的超新星和较近的Ia型超新星非常相似。结合以前对较近距离的Ia型超新星的观测数据[2,5]，这些新测量表明我们可能生活在一个质量密度偏低的宇宙之中。

SN1997ap于世界时(UT)1997年3月5日被超新星宇宙学项目团队发现。位于智利的托洛洛山美洲天文台(CTIO)4米望远镜在两个晚上的搜寻中总共发现了16颗新的超新星。搜寻技术能够在这些高红移超新星处于光变曲线上升阶段的时候发现它们，这就保证了发现的日期。因此我们可以安排对这些暂现的超新星进行进一步的测光和光谱观测[1]。利用CTIO、WIYN、ESO 3.6米和INT的望远镜，我们按

with scheduled R-, I- and some B-band photometry at the CTIO, WIYN, ESO 3.6-m, and INT telescopes, and with spectroscopy at the ESO 3.6-m and Keck II telescopes. (Here WIYN is the Wisconsin, Indiana, Yale, NOAO Telescope, ESO is the European Southern Observatory, and INT is the Isaac Newton Telescope.) In addition, SN1997ap was followed with scheduled photometry on the Hubble Space Telescope (HST).

Figure 1 shows the spectrum of SN1997ap, obtained on 14 March 1997 UT with a 1.5-h integration on the Keck II 10-m telescope. There is negligible ($\lesssim 5\%$) host-galaxy light contaminating the supernova spectrum, as measured from the ground- and space-based images. When fitted to a time series of well-measured nearby type Ia supernova spectra[9], the spectrum of SN1997ap is most consistent with a "normal" type Ia supernova at redshift $z = 0.83$ observed 2 ± 2 supernova-restframe days (~4 observer's days) before the supernova's maximum light in the rest-frame B band. It is a poor match to the "abnormal" type Ia supernovae, such as the brighter SN1991T or the fainter SN1986G. For comparison, the spectra of low-redshift, "normal" type Ia supernovae are shown in Fig. 1 with wavelengths redshifted as they would appear at $z = 0.83$. These spectra show the time evolution from 7 days before, to 2 days after, maximum light.

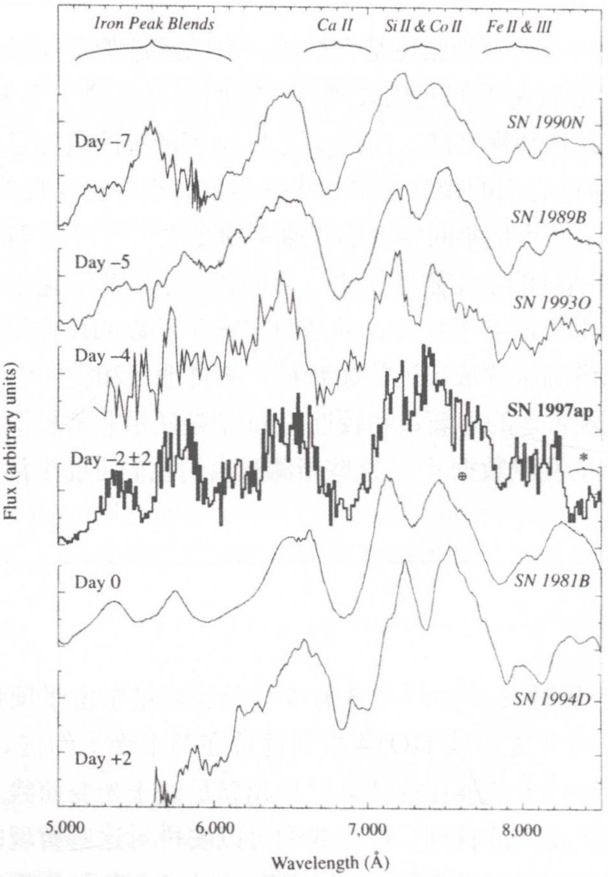

Fig. 1. Spectrum of SN1997ap placed within a time sequence of five "normal" type Ia supernovae. The

计划在 R、I 及 B 波段对超新星进行了测光从而得到光变曲线，同时还用 ESO 3.6 米和凯克 II 望远镜拍摄了光谱。(这里的 WIYN 是指威斯康星大学–印第安纳大学–耶鲁大学–美国国家光学天文台望远镜；ESO 是指欧洲南方天文台；INT 是指艾萨克 · 牛顿望远镜。) 此外，我们还安排哈勃空间望远镜 (HST) 对 SN1997ap 进行测光。

图 1 是 SN1997ap 的光谱，它是由凯克 II 10 米天文望远镜于 1997 年 3 月 14 日 UT 持续 1.5 小时的观测数据积分而成。地面以及空间望远镜测量到的图像显示，寄主星系对超新星光谱的污染可以忽略不计 (≤5%)。我们把 SN1997ap 的光谱与一系列较近且已充分测量过的 Ia 型超新星光谱做时间序列拟合，发现它的光谱与红移 $z = 0.83$、在 B 波段极大亮度前 2±2 日 (超新星静止系，约为 4 个观测者日) 观测的“正常” Ia 型超新星最为一致。SN1997ap 的光谱与其他“非正常” Ia 型超新星 (例如较亮的 SN1991T 或较暗的 SN1986G) 的光谱并不匹配。图 1 中为了方便比较，低红移的“正常” Ia 型超新星的光谱被红移到 $z = 0.83$ 处。这些光谱显示了超新星从最大亮度的前 7 天到后 2 天的时间演化。

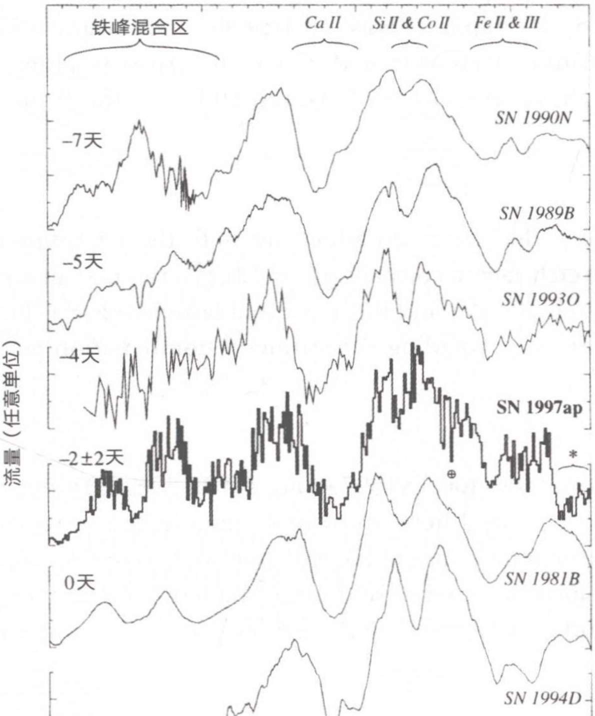

图 1. SN1997ap 的光谱与五个“正常” Ia 型超新星光谱放在一个时间序列中。SN1997ap 的光谱以 12.5 Å data for SN1997ap have been binned by 12.5 Å ; the time series of spectra of the other supernovae[17-21] (the spectrum of SN1993O was provided courtesy of the Calán/Tololo Supernova Survey) are given as they would appear redshifted to $z = 0.83$. The spectra show the evolution of spectral features between 7 rest-frame days before, and 2 days after, rest-frame B-band maximum light. SN1997ap matches best at 2 ± 2 days before maximum light. The symbol $\oplus$ indicates an atmospheric absorption line and * indicates a region affected by night-sky line subtraction residuals. The redshift of $z = 0.83 \pm 0.005$ was determined from the supernova spectrum itself, as there were no host galaxy lines detected.

Figure 2 shows the photometry data for SN1997ap, with significantly smaller error bars for the HST observations (Fig. 2a) than for the ground-based observations (Fig. 2b and c). The width of the light curve of a type Ia supernova has been shown to be an excellent indicator of its intrinsic luminosity, both at low redshift[2-4] and at high redshift[5]: the broader and slower the light curve, the brighter the supernova is at maximum. We characterize this width by fitting the photometry data to a "normal" type Ia supernova template light curve that has its time axis stretched or compressed by a linear factor, called the "stretch factor"[1,5]; a "normal" supernova such as SN1989B, SN1993O or SN1981B in Fig. 1 thus has a stretch factor of $s \approx 1$. To fit the photometry data for SN1997ap, we use template U- and B-band light curves that have first been $1+z$ time-dilated and wavelength-shifted ("*K*-corrected") to the R- and I-bands as they would appear at $z = 0.83$ (see ref. 5 and P.N. *et al.*, manuscript in preparation). The best-fit stretch factor for all the photometry of Fig. 2 indicates that SN1997ap is a "normal" type Ia supernova: $s = 1.03 \pm 0.05$ when fitted for a date of maximum at 16.3 March 1997 UT (the error-weighted average of the best-fit dates from the light curve, 15.3 ± 1.6 March 1997 UT, and from the spectrum, 18 ± 3 March 1997 UT).

It is interesting to note that we could alternatively fit the $1+z$ time dilation of the event while holding the stretch factor constant at $s = 1.0^{+0.05}_{-0.14}$ (the best fit value from the spectral features obtained in ref. 10). We find that the event lasted $1+z = 1.86^{+0.31}_{-0.09}$ times longer than a nearby $s = 1$ supernova, providing the strongest confirmation yet of the cosmological nature of redshift[9,11,12].

The best-fit peak magnitudes for SN1997ap are $I = 23.20 \pm 0.07$ and $R = 24.10 \pm 0.09$. (All magnitudes quoted or plotted here are transformed to the standard Cousins[13] R and I bands.) These peak magnitudes are relatively insensitive to the details of the fit: if the date of maximum is left unconstrained or set to the date indicated by the best-match spectrum, or if the ground- and space-based data are fitted alone, the peak magnitudes still agree well within errors.

为区间合并；其他超新星的光谱[17-21]（SN1993O 的光谱数据由 Calán/Tololo 超新星巡天提供）都被红移到 $z = 0.83$ 处。这些光谱反映了静止系 B 波段光强达到峰值的 7 天前至 2 天后之间的光谱特征变化。SN1997ap 的数据与最大亮度前 2 ± 2 天的光谱数据最吻合。符号⊕表示大气吸收线，* 表示受夜天光抵扣残余影响的区域。红移 $z = 0.83 \pm 0.005$ 得自超新星光谱，我们并没有检测到寄主星系的谱线。

图 2 显示的是超新星 SN1997ap 的测光数据。哈勃空间望远镜的观测（图 2a）误差显著小于地面望远镜的观测（图 2b 和 2c）。Ia 型超新星光变曲线的宽度被证明是“本征光度”的绝佳表征，无论是在低红移[2-4]还是在高红移[5]处：超新星的光变曲线越宽、变化越慢，那么最大亮度就越高。我们通过将测光数据与“正常”Ia 型超新星的光变曲线模板进行拟合来得到这个宽度，其中模板的时间轴由一个称为“伸展因子”[1,5]的线性参数进行“拉伸”或“压缩”。图 1 中的“正常”超新星 SN1989B、SN1993O 及 SN1981B 的伸展因子 s 约等于 1。为了拟合 SN1997ap 的测光数据，我们使用 U 和 B 波段的光变曲线作为模板，将其经过 $1+z$ 倍的时间拉伸和波长平移（即“K 修正”）之后移动到 R 和 I 波段，就像它们在红移 0.83 处一样（见参考文献 5 和纽金特等人正在撰写的文章）。利用图 2 中所有测光数据对延展因子进行拟合得到 $s = 1.03 \pm 0.05$，这表明 SN1997ap 是一个“正常”的 Ia 型超新星：拟合的亮度极大值日期为 1997 年 3 月 16.3 日 UT（根据光变曲线得到的误差加权平均值为 1997 年 3 月 15.3 ± 1.6 日 UT，根据光谱得到的结果为 1997 年 3 月 18 ± 3 日 UT）。

值得一提的是，我们也可以保持伸展因子 $s = 1.0^{+0.05}_{-0.14}$ 不变（这个最佳拟合值来自文献 10 中的光谱数据），然后对事件的时间膨胀因子 $1+z$ 进行拟合。我们发现 SN1997ap 爆发事件的持续时间是一颗较近超新星（$s = 1$）的 $1+z = 1.86^{+0.31}_{-0.09}$ 倍，这一点为红移的宇宙学属性提供了迄今最强的确认[9,11,12]。

超新星 SN1997ap 的峰值星等最佳拟合值为 $I = 23.20 \pm 0.07$ 以及 $R = 24.10 \pm 0.09$。（在本文中，所有提到和绘出的星等都已转换为标准的库森[13]R 和 I 波段星等。）这些峰值星等对拟合的细节并不敏感：如果我们不限制最大值日期或是以最佳匹配光谱来设定最大值日期，或者是只用地面观测数据或空间观测数据来单独拟合，拟合的星等峰值仍然在误差以内。

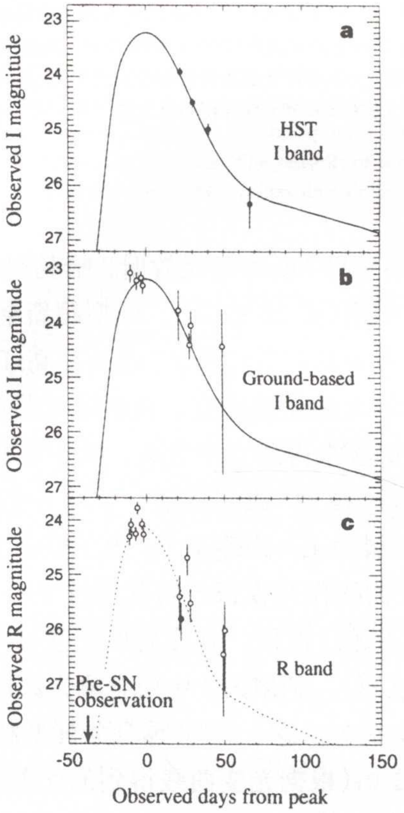

Fig. 2. Photometry points for SN1997ap. **a**, As observed by the HST in the F814W filter; **b**, as observed with ground-based telescopes in the Harris I filter; and **c**, as observed with the ground-based telescopes in the Harris R filter (open circles) and the HST in the F675W filter (filled circle); with all magnitudes corrected to the Cousins I or R systems[13]. The solid line shown in both **a** and **b** is the simultaneous best fit to the ground- and space-based data to the K-corrected, $(1+z)$ time-dilated Leibundgut B-band type Ia supernova template light curve[22], and the dotted line in **c** is the best fit to a K-corrected, time-dilated U-band type Ia supernova template light curve. The ground-based data was reduced and calibrated following the techniques of ref. 5, but with no host-galaxy light subtraction necessary. The HST data was calibrated and corrected for charge-transfer inefficiency following the prescriptions of refs 23, 24. K-corrections were calculated as in ref. 25, modified for the HST filter system. Correlated zero-point errors are accounted for in the simultaneous fit of the light curve. The errors in the calibration, charge-transfer inefficiency correction and K-corrections for the HST data are much smaller (~4% total) than the contributions from the photon noise. No corrections were applied to the HST data for a possible ~4% error in the zero points (P. Stetson, personal communication) or for nonlinearities in the WFPC2 response[26], which might bring the faintest of the HST points into tighter correspondence with the best-fit light curve in **a** and **c**. Note that the individual fits to the data in **a** and **b** agree within their error bars, providing a first-order cross-check of the HST calibration.

The ground-based data show no evidence of host-galaxy light, but the higher-resolution HST imaging shows a marginal detection (after co-adding all four dates of observation) of a possible $I = 25.2 \pm 0.3$ host galaxy 1 arcsec from the supernova. This light does not contaminate the supernova photometry from the HST and it contributes negligibly to the ground-based photometry. The projected separation is ~6 kpc (for $\Omega_{\mathrm{M}} = 1$, $\Omega_{\Lambda} = 0$ and $h_0 = 0.65$, the dimensionless cosmological parameters describing the mass density,