Many past studies of cosmological $\gamma$-ray bursts (GRBs) have been limited because of the large distance to typical GRBs, resulting in faint afterglows. There has long been a recognition that a nearby GRB would shed light on the origin of these mysterious cosmic explosions, as well as the physics of their fireballs. However, GRBs nearer than $z = 0.2$ are extremely rare, with an estimated rate of localisation of one every decade. Here, we report the discovery of bright optical afterglow emission from GRB 030329. Our prompt dissemination and the brilliance of the afterglow resulted in extensive followup (more than 65 telescopes) from radio through X-ray bands, as well as measurement of the redshift, $z = 0.169$. The $\gamma$-ray and afterglow properties of GRB 030329 are similar to those of cosmological GRBs (after accounting for the small distance), making this the nearest known cosmological GRB. Observations have already securely identified the progenitor as a massive star that exploded as a supernova, and we anticipate further revelations of the GRB phenomenon from studies of this source.

On 2003 March 29, 11h37m14s.67 UT, GRB 030329 triggered all three instruments on board the High Energy Transient Explorer II (HETE-II). About 1.4 hours later, the HETE-II team disseminated via the GRB Coordinates Network (GCN) the 4-arcminute diameter localisation by the Soft X-ray Camera (SXC). We immediately observed the
error-circle with the Wide Field Imager (WFI) on the 40-inch telescope at Siding Spring Observatory under inclement conditions (nearby thunderstorms). Nevertheless, we were able to identify a bright source not present on the Digitised Sky Survey (Figure 1) and rapidly communicated the discovery to the community. The same source was independently detected by the RIKEN automated telescope.

With a magnitude of 12.6 in the $R$ band at 1.5 hours, the optical afterglow of GRB 030329 is unusually bright. At the same epoch, the well-studied GRB 021004 was $R \sim 16$ mag, and the famous GRB 990123 was $R \sim 17$ mag. The brightness of this afterglow triggered observations by over 65 optical telescopes around the world, ranging from sub-metre apertures to the Keck I 10-metre telescope. Unprecedented bright emission at radio, millimetre, sub-millimetre, and X-ray was also reported (Figure 2).

Greiner et al. made spectroscopic observations with the Very Large Telescope (VLT) in Chile approximately 16 hours after the GRB and, based on absorption as well as emission lines, announced a redshift of $z = 0.1685$. From Keck spectroscopic observations obtained 8 hours later (Figure 3) we confirm the VLT redshift, finding $z = 0.169 \pm 0.001$. We note that the optical afterglow of GRB 030329 was, at 1.5 hours, approximately the same brightness as the nearest quasar, 3C 273 ($z = 0.158$); it is remarkable that such a large difference in the mass of the engine can produce an optical source with the same luminosity.

With a duration of about 25-s and multi-pulse profile, GRB 030329 is typical of the long duration class of GRBs. The fluence of GRB 030329, as detected by the Konus experiment, of $1.6 \times 10^{-4}$ erg cm$^{-2}$ (in the energy range 15-5000 keV) places this burst in the top 1% of GRBs.

At a redshift of 0.169, GRB 030329 is the nearest of the cosmological GRBs studied in the 6-year history of afterglow research. Assuming a Lambda cosmology with $H_0 = 71$ km/s/Mpc, $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$, the angular-diameter distance is $d_A = 589$ Mpc and the luminosity distance is $d_L = 805$ Mpc. The isotropic $\gamma$-ray energy release, $E_{\gamma,\text{iso}} \sim 1.3 \times 10^{52}$ erg, is typical of cosmological GRBs. Likewise, the optical and radio luminosities of the afterglow of GRB 030329 are not markedly different
from those of cosmological GRBs. In particular, the extrapolated isotropic X-ray luminosity at \( t = 10 \) hr is \( L_{X,\text{iso}} \sim 6.4 \times 10^{45} \text{ erg s}^{-1} \), not distinctly different from that of other X-ray afterglows (e.g. ref. 15).

Nonetheless, two peculiarities about the afterglow of GRB 030329 are worth noting. First, the optical emission steepens from \( f(t) \propto t^{-\alpha} \) with \( \alpha_1 = 0.873 \pm 0.025 \) to \( \alpha_2 = 1.97 \pm 0.12 \) at epoch \( t_* = 0.481 \pm 0.033 \text{ d} \) (Figure 4; see also ref. 16). This change in \( \alpha \) is too large to be due to the passage of a cooling break (\( \Delta \alpha = 1/4 \); ref. 17) through the optical bands. On the other hand, \( \alpha \sim 2 \) is typically seen in afterglows following the so-called “jet-break” epoch (\( t_j \)). Before this epoch, the explosion can be regarded as isotropic, and following this epoch the true collimated geometry is manifested. Such an early jet break would imply a substantially-lower energy release than \( E_{\gamma,\text{iso}} \).

If \( t_* \sim t_j \) then using the formalism and adopting the density and \( \gamma \)-ray efficiency normalisations of Frail et al.\(^{14}\) we estimate the true \( \gamma \)-ray energy release to be \( E_\gamma \sim 3 \times 10^{49} \) erg. This estimate is \( 4\sigma \) lower than the “standard energy” of \( 5 \times 10^{50} \) erg found by Frail et al.\(^{14}\) The geometric-corrected x-ray luminosity\(^{15}\) would also be the lowest of all x-ray afterglows. If the above interpretation is correct then GRB 030329 may be the missing link between cosmological GRBs and the peculiar GRB 980425\(^{18}\) (\( E_{\gamma,\text{iso}} \sim 10^{48} \) erg) which has been associated with SN 1998bw at \( z = 0.0085 \).

Second, the decay of the optical afterglow is marked by bumps and wiggles (e.g. ref. 19). These features could be due to inhomogeneities in the circumburst medium or additional shells of ejecta from the central engine. In either case, the bumps and wiggles complicate the simple jet interpretation offered above. We note that if the GRB had been more distant, and hence the afterglow fainter, then the break in the light curve would likely have been interpreted as the jet break without question.

The proximity of GRB 030329 offers us several new opportunities to understand the origin of GRBs. Red bumps in the light curve have been seen in several more-distant (\( z \sim 0.3 \) to 1) GRB afterglows (e.g. refs 20,21) and interpreted as underlying SNe that caused the GRBs. While these red bumps appeared to be consistent with a SN light curve, prior to GRB 030329, it had not yet been unambiguously demonstrated that they were indeed SNe. As this paper was being written, a clear spectroscopic signature for an underlying SN has been identified in the optical afterglow of GRB 030329.\(^5\) Our
own spectroscopy at Palomar and Keck confirm the presence of these SN features. This demonstrates once and for all that the progenitors of at least some GRBs are massive stars that explode as SNe.

However, there remain a number of issues still to be resolved, relating to the physics of GRB afterglows and the environment around the progenitor. The “fireball” model of GRB afterglows predicts a broad-band spectrum from centimetre wavelengths to x-rays that evolves as the GRB ejecta expand and sweep up the surrounding medium. Testing this model in detail has in the past been difficult, primarily due to both low signal-to-noise and interstellar scintillation at the longer wavelengths, from which come the majority of spectral and temporal coverage of the afterglow evolution (e.g. refs. 22, 23). GRB 030329, with bright emission at all wavelengths (Figure 2), and limited scintillation (due to the larger apparent size) will allow astronomers to test the predictions of the fireball model with unprecedented precision through the time evolution of the broad-band spectrum, the angular size of the fireball, and its proper motion (if any). It has been long predicted that if the progenitors of GRBs are massive stars, the circumburst medium should be rich and inhomogenous, but it has been difficult to find evidence for this. However, for GRB 030329, it should be possible to trace the distribution of circumburst material and determine the environment of the progenitor.

Even in the Swift (launch December 2003) era, we expect only one such nearby ($z < 0.2$) GRB every decade (scaling from ref. 1). Thus GRB 030329, the nearest of the cosmological GRBs to date, has given astronomers a rare opportunity to be up close and personal with a GRB and its afterglow. We eagerly await reports of the many experiments that have been and will be conducted to shed new light on the GRB phenomenon.

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**Figure 1:** Discovery of the bright optical afterglow of GRB 030329. The 600-s exposure taken with the Wide-Field Imager at the 40-inch telescope of the Siding Spring Observatory (SSO) using an $R$-filter (a) started at March 29, 13$^h$05$^m$ UT, 2003, about 1.5 hours after the $\gamma$-ray event, and was strongly affected by clouds. Nevertheless, comparison of the SSO image with the Second Digitised Sky Survey (b) in the $R_F$-band at the telescope allowed us to identify a 12th magnitude afterglow (arrowed) within the 4-arcmin HETE-II SXC error-circle$^2$ (marked). The position of the optical afterglow was determined with respect to USNO-A2.0 and found to be $\alpha_{2000} = 10^h44^m59^s.95$, $\delta_{2000} = +21^\circ31'17''.8$ with uncertainty of 0.5 arcsec in each axis.

**Figure 2:** A snapshot spectral flux distribution of the afterglow of GRB 030329. This broad-band spectrum of the afterglow at 0.5 days after the GRB$^{10-12,25-28}$ demonstrates both the brightness of the afterglow, with the resulting spectral coverage. Solid circles represent measurements made near the nominal time; open circles represent measurements extrapolated to the nominal time assuming evolution appropriate for a constant-density medium; this figure is therefore meant to be illustrative rather than entirely accurate. A simple fit of an afterglow broad-band spectrum yields the following spectral parameters (we use the convention and symbols of ref. 17): synchrotron self-absorption frequency, $\nu_a \sim 25$ GHz; peak frequency, $\nu_m \sim 1270$ GHz; cooling frequency, $\nu_c \sim 6.2 \times 10^{14}$ Hz; peak flux, $f_m \sim 65$ mJy; and electron energy index, $p \sim 2$. The physical parameters inferred are as follows: explosion energy, $E \sim 5.7 \times 10^{51}$ erg; ambient density, $n \sim 5.5$ atom cm$^{-3}$; electron energy fraction, $\epsilon_e \sim 0.16$ and magnetic energy fraction, $\epsilon_B \sim 0.012$.

**Figure 3:** Spectrum of the optical afterglow. The observation was made with the Low Resolution Imaging Spectrometer on the Keck I telescope, using the 400 lines/mm grism on the blue side, giving an effective resolution of 4.2Å. Our observation consisted of a single 600 second exposure on the afterglow. We reduced and extracted the spectra in the standard manner using IRAF. No standard star observations were available, so we have simply fit and normalised the continuum before smoothing with a 4Å boxcar. We identify narrow emission lines from [O II], H$\beta$ and [O III], and absorption lines from Mg II at a mean redshift, $z = 0.169 \pm 0.001$, making GRB 030329 the lowest-redshift cosmological GRB. These emission lines are typical of star-forming galaxies, whereas the absorption
lines are caused by gas in the disk of the galaxy. In addition, we identify Ca II at \( z \approx 0 \), presumably due to clouds in our own Galaxy.

**Figure 4:** Light-curve of the optical afterglow of GRB 030329. This \( R \)-band light curve spans from our discovery to approximately 1 day after the GRB. Due to the brightness of the GRB, errors in the measurements are smaller than the plotted points. In addition to measurements gleaned from the GCN Circulars,\(^{27,29}\) we include the following measurements from observations with the SSO 40-inch telescope with WFI in 2003 March: 29.5491, \( R = 12.649 \pm 0.015 \) mag; 29.5568, \( R = 12.786 \pm 0.017 \) mag; 30.5044, \( R = 16.181 \pm 0.010 \) mag; 30.5100, \( R = 16.227 \pm 0.009 \) mag. These measurements are relative to field stars calibrated by Henden.\(^{30}\)
Figure 1.
Figure 2.
Figure 3.
Figure 4.