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An enigmatic long-lasting γ -ray burst not accompanied by a bright supernova

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Gamma-ray bursts (GRBs) are short, intense flashes of soft γ -rays coming from the distant Universe. Long-duration GRBs (those lasting more than ~ 2 s) are believed to originate from the deaths of massive stars¹, mainly on the basis of a handful of solid associations between GRBs and supernovae^{2–7}. GRB 060614, one of the closest GRBs discovered, consisted of a 5-s hard spike followed by softer, brighter emission that lasted for ~ 100 s (refs 8, 9). Here we report deep optical observations of GRB 060614 showing no emerging supernova with absolute visual magnitude brighter than $M_V = -13.7$. Any supernova associated with GRB 060614 was therefore at least 100 times fainter, at optical wavelengths, than the other supernovae associated with GRBs¹⁰. This demonstrates that some long-lasting GRBs can either be associated with a very faint supernova or produced by different phenomena.

Following the discovery of the X-ray and optical afterglow of GRB 060614⁹, we observed it with the European Southern Observatory (ESO) 8.2 m Very Large Telescope (VLT). The spectrum of the host galaxy exhibits nebular emission lines (Fig. 1), which reveal ongoing star formation and the presence of young, massive stars. The specific star formation rate, normalized to the host luminosity (B-band magnitude $M_B = -15.5$), is about $2 M_\odot \text{ yr}^{-1} L_*^{-1}$, where M_\odot is the solar mass and L_* is the typical luminosity of field galaxies. This value is comparable to that exhibited by the Milky Way, and is at the low end of the distribution found for long-duration GRB hosts¹¹. The galaxy is also fainter than most GRB hosts¹².

Starting 15 h after the burst, we monitored the light curve of the optical transient associated with GRB 060614. Deep observations obtained in the R band (roughly corresponding to the V band in the GRB rest frame) up to 65 d after the burst did not reveal the emergence of a supernova component (Fig. 2; see also refs 13, 14); such a component has been often observed in a number of nearby long-duration GRBs. Our data are consistent with no supernova contribution (blue line). Adopting as a template the light curve of SN 1998bw², we constrain the brightness of a supernova coincident with GRB 060614 to be at least 5.6 mag fainter than the template (3σ limit; green lines in Fig. 2). This corresponds to a peak absolute magnitude $M_V > -13.5$. Similar limiting magnitudes are obtained adopting different supernova light curve shapes. A brighter supernova (yellow lines in Fig. 2) would provide a totally inadequate fit. The faintness of a possible supernova at optical

wavelengths was further confirmed by a series of about ten spectra obtained at the VLT in the 4,500–8,000 Å wavelength range, between 2006 June 15 and 2006 July 30. None of them shows the broad undulations due to the very high expansion velocities ($\sim 30,000 \text{ km s}^{-1}$) typical of the supernovae¹⁵ associated with GRBs.

Such faintness cannot be due to dust extinction. First, the afterglow optical spectra are not particularly red (from our BVRIJK photometry we measure a spectral index $\beta = 0.94$ at ~ 1.7 d after the GRB). The afterglow is also bright in the ultraviolet⁹, where extinction would be more severe. X-ray spectra (V.M. *et al.*, manuscript in preparation) also show little absorbing material along the line of sight (yielding a rest-frame hydrogen column density $N_{\text{H}} < 2 \times 10^{20} \text{ cm}^{-2}$ at 90% confidence level). Furthermore, by modelling the broad-band optical/X-ray spectral energy distribution (see Supplementary Fig. 1), we can estimate that the source was affected by less than 0.2 mag of extinction in the observed R band. Allowing for this amount of extinction, we can refine our limit for the supernova peak magnitude to $M_V > -13.7$.

So far only type-Ib/c events have been clearly associated with GRBs¹ and, had the progenitor of GRB 060614 been one of them, its expected colour at maximum light would be $B - V \approx 0.5 \pm 0.1$, as measured in well-observed events such as SN 2006aj¹⁰, SN 2002ap¹⁶ and SN 1998bw², as well in several other type-Ib/c SNe. From the tables of ref. 17, we find that this colour corresponds to an effective temperature $T \approx 6,500 \text{ K}$, which, combined with the lower limit to the absolute magnitude, provides a strict upper limit to the bolometric luminosity, at maximum light, of $L < 10^{41} \text{ erg s}^{-1}$. Therefore the radius of the emitting region is constrained to be $R \approx \sqrt{L/(4\pi\sigma T^4)} < 2.8 \times 10^{14} \text{ cm}$ (where σ is the Stefan-Boltzmann constant). As the rise times to maximum light of type-Ib/c supernovae range between 10 and 20 d (refs 10, 18-20) in the V band, the upper limit to the radius implies an upper limit to the expansion velocity in the range 1,600–3,200 km s^{-1} . This value is an order of magnitude smaller than that observed in SNe associated with GRBs^{7,15}.

The low expansion velocity and the faint luminosity implied for a possible supernova progenitor are reminiscent of a class of very faint core-collapse supernovae recently discovered²¹ in the local Universe. They are of type II, have absolute magnitudes at maximum in the range $-13 > M_V > -15$, and show very small expansion velocities ($\sim 1,000 \text{ km s}^{-1}$). The properties of such objects may well be consistent with the available data on GRB 060614.

Faint type-II SNe have been interpreted in terms of the collapse of massive stars with an explosion energy so small that most of ^{56}Ni falls back onto the compact stellar remnant²². Such supernovae share properties with the present case, both in terms of observational characteristics and because they are expected to give rise to a black hole (which is believed to be necessary for the production of a GRB). However, the possibility that such supernova progenitors are able to produce GRBs has yet to be explored. In particular, the stellar envelope would need to be absent for the relativistic jets to emerge out of the star. GRB 060614 might thus be an example of a fallback supernova of type Ib/c. The small amount of nickel ($< 10^{-3} M_{\odot}$), responsible for the very low luminosity, might possibly also provide little heating to the ejecta, leading to an unusually low temperature ($T \approx 2,000$ K) and allowing for larger velocities (as $v \propto T^{-2}$). In any case, GRB 060614 may be the prototype of a new class of GRBs originating from a new kind of massive stars death, different from those producing both classical long-duration (associated with bright type-Ib/c supernovae) and short-duration (possibly originating in binary system mergers²³) GRBs. Some evidence for this idea comes from the high-energy properties of this GRB, which contemporaneously exhibits features typical of both the long and short GRB classes⁸. Indeed, scenarios in which the GRB was not directly connected to a supernova explosion²⁴ cannot be excluded by our data (though they are not required). For example, our data would be compatible with a supernova exploding before the GRB²⁵. Also, a binary merger mechanism²⁶, similar to that proposed to power short-duration GRBs, or some type of collapsar model²⁷, are not expected to produce a supernova. These results challenge the commonly accepted scenario, in which long-duration GRBs are produced only together with very bright supernova explosions. Not all GRBs are produced in such a way.

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Supplementary information is linked to the online version of the paper at www.nature.com/nature.

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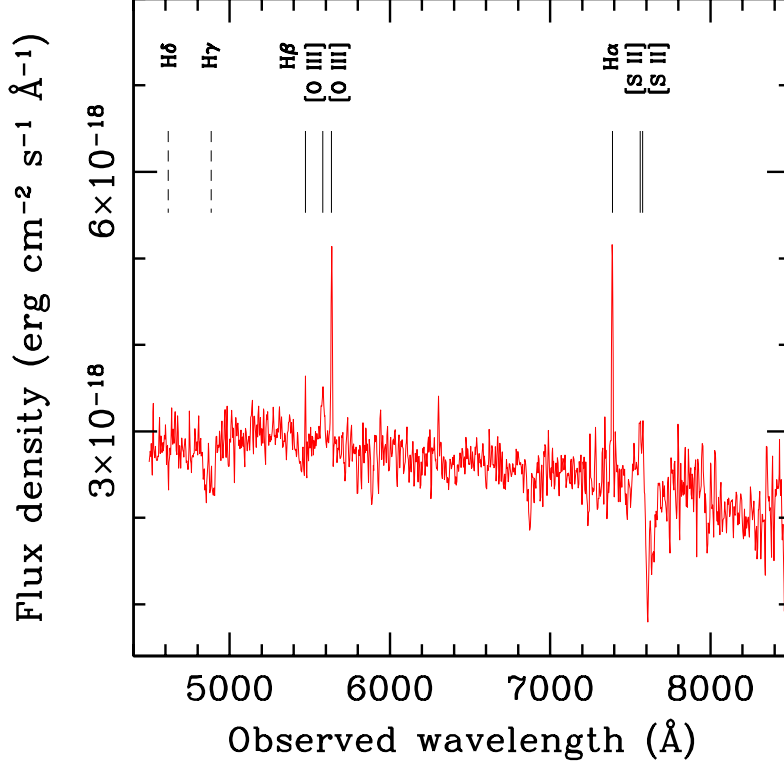


Figure 1 | Spectrum of the host galaxy of GRB 060614. This is the average of several observations taken with the VLT equipped with the FORS2 spectrograph in the period 2006 June 20 to July 30. From the emission features (marked with solid bars) we infer $z = 0.1254 \pm 0.0005$. This confirms the redshift proposed in ref. 28. $H\gamma$ and $H\delta$ are seen in absorption (dashed bars). The flux from the $H\alpha$ line, not corrected for internal extinction, amounts to $4.1 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$ (corrected for slit loss). This corresponds to an unobscured star formation rate of $1.3 \times 10^{-2} M_{\odot} \text{ yr}^{-1}$. Given the faintness of the galaxy ($M_B \approx -15.5$), however, the specific star formation rate ($2 M_{\odot} \text{ yr}^{-1} L_*^{-1}$, assuming for the absolute B-band magnitude of field galaxies $M_B^* = -21$), is not negligible. From the observed flux of the [O III] lines and the limits on [N II], we infer a metallicity larger than $\sim 1/20$ solar.

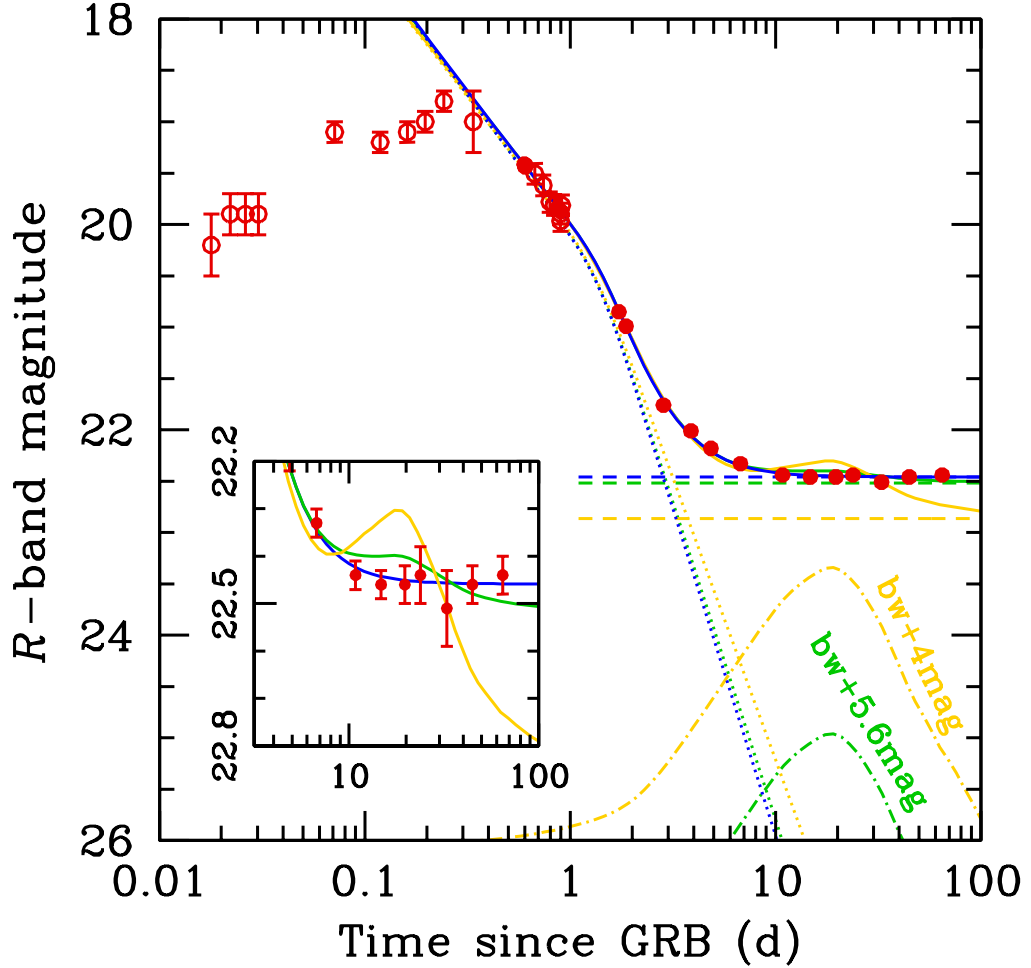
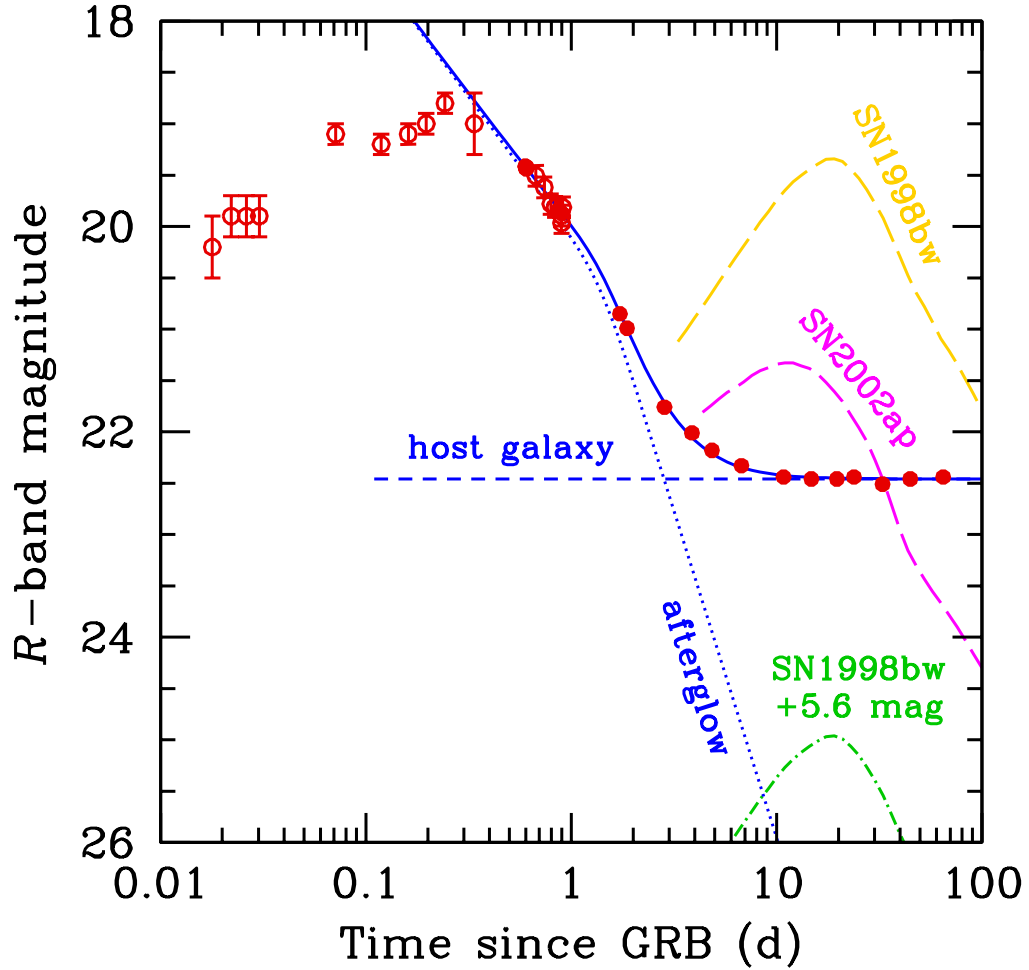


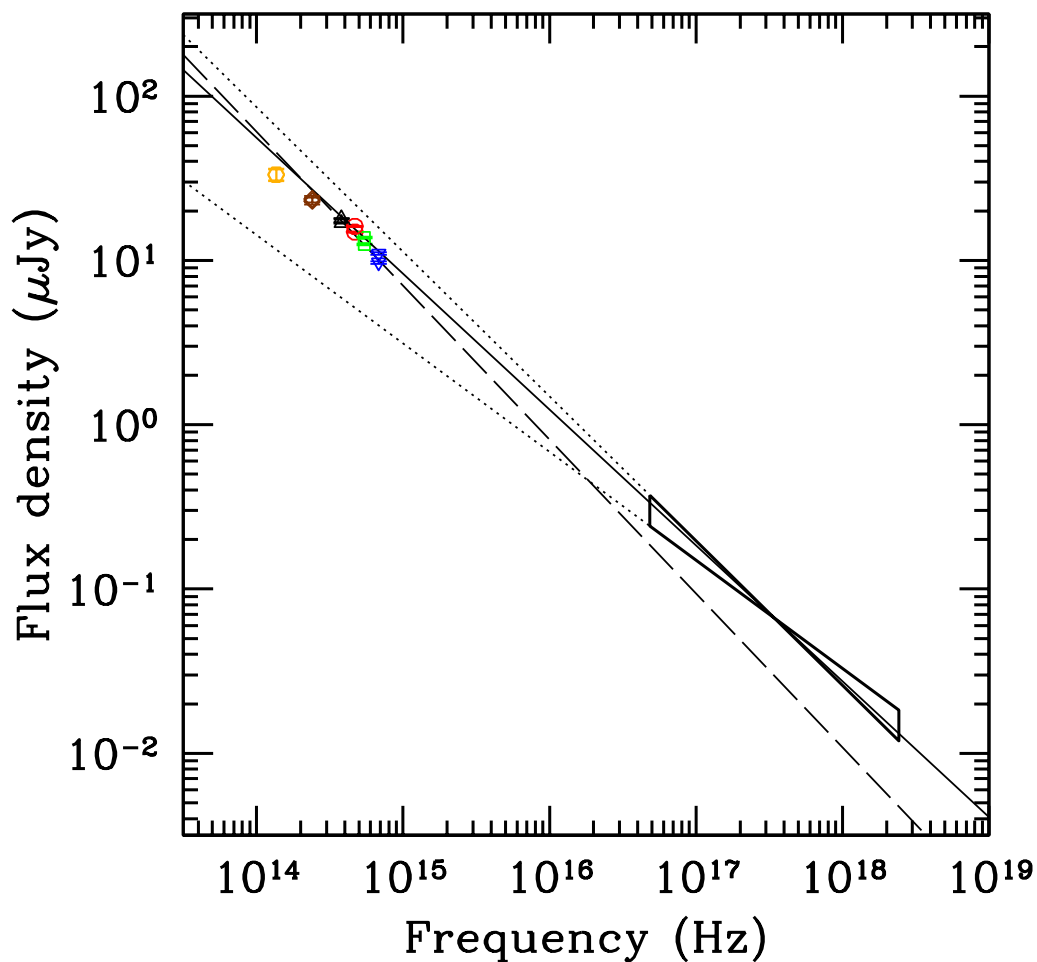
Figure 2 | R-band light curve of the GRB 060614 afterglow. Red open circles show data from the literature^{13,14,29} (not used in the fits); red filled circles represent our VLT data (see Supplementary Table 1). Error bars (smaller than symbols for most of our data) show the 1σ errors. Photometry was performed adopting large apertures in order to include all the flux from the host galaxy. Flux calibration was achieved by observing several Landolt standard fields. The data were modelled as the sum (solid lines) of three components: the afterglow (dotted lines), the host (dashed lines) and a supernova akin to SN 1998bw but rescaled in flux ('bw'; dot-dashed lines). The different colours correspond to different contributions from the

supernova: no contribution (blue), a supernova fainter by 5.6 mag (green), and a supernova fainter by 4 mag (yellow). The model shown by green lines corresponds to the brightest supernova allowed by our data, $M_V > -13.5$, at the 3σ level. At the 2σ level, the limit is $M_V > -12.9$. The model shown by the yellow lines is clearly inadequate. The inset shows an expanded version of the plot around the peak of a putative supernova. The afterglow component is described by a broken power law with decay indices $\alpha_1 = 1.08 \pm 0.03$ and $\alpha_2 = 2.48 \pm 0.07$, respectively before and after the break at $t_{\text{break}} = 1.39 \pm 0.04$ d ($\chi^2/\text{d.o.f} = 15.5/20$). Interpreting this as a jet break, the inferred jet half-opening angle is $\vartheta \approx 12^\circ$.



Extra figure | Comparison of the light curve of the GRB 060614 afterglow and those of SN 1998bw and SN 2006aj. The yellow and magenta long-dashed lines show the light curves of two supernovae previously found to be associated with other GRBs reported at $z = 0.1254$. The green dot-dashed line shows the brightest supernova allowed by our data at the 3σ level. The contribution of the host galaxy (short-dashed line) and of the afterglow (dotted line) are also indicated. The data are the same as in Fig. 2.

Supplementary material for “An enigmatic long-lasting γ -ray burst not accompanied by a bright supernova”.



Supplementary Figure 1 | Estimate of the reddening correction. We interpret the afterglow radiation as due to synchrotron emission, as usually assumed for GRB afterglows. In order to build the optical spectral energy distribution (SED), we adopt our $BVRIJK$ photometry and take the X-ray data from the work by V.M. *et al.* (in preparation). Using our best-fit

light curve we report all data at the common epoch $t = 1.73$ days after the burst (the time around which our measurements cluster). After correcting for the Galactic extinction ($A_V = 0.07$ mag), the optical spectrum is well fit by a power law ($F_\nu \propto \nu^{-\beta}$) with index $\beta = 0.94 \pm 0.08$ (dashed line). At the same time, the X-ray spectrum is described by a power law with index $\beta = 0.77 \pm 0.11$. Supplementary Figure 1 shows the broad-band SED at this epoch. As can be seen, the optical and X-ray data belong to the same power-law segment. The common origin of the two components is also confirmed by their similar temporal properties. Assuming an SMC-like extinction curve, to make the optical data match exactly the X-ray flux, an amount of extinction $A_V = 0.08$ mag is required. Since the rest-frame V band corresponds to the R band, this is also the amount of extinction suffered by our measurements. Assuming different extinction curves, the absorption corresponding to the observed R band does not change significantly and is always less than 0.1 mag.

Supplementary Table 1 | Log of observations. The time t_0 indicates the GRB trigger time, 2006 June 14.53042 UT. Errors are given at the 1- σ confidence level.

Mean date (UT)	$t - t_0$ (days)	Filter	Exposure (s)	Airmass	Seeing ($''$)	Instrument	Magnitude
2006 Jun 16.27492	1.74450	<i>B</i>	4×90	1.23	0.60	VLT+FORS1	21.72±0.02
2006 Sep 02.05099	79.52057	<i>B</i>	10×120	1.25	1.30	VLT+FORS1	23.62±0.15
2006 Jun 16.25076	1.72034	<i>V</i>	2×120	1.30	0.55	VLT+FORS1	21.20±0.01
2006 Jun 17.36557	2.83515	<i>V</i>	4×90	1.14	0.50	VLT+FORS1	22.16±0.02
2006 Jun 18.39119	3.86077	<i>V</i>	6×180	1.17	0.80	VLT+FORS1	22.47±0.02
2006 Jul 08.33006	23.79964	<i>V</i>	2×120	1.16	1.20	VLT+FORS1	22.75±0.07
2006 Jul 17.31686	32.78644	<i>V</i>	5×120	1.17	1.10	VLT+FORS1	22.74±0.09
2006 Jun 15.12757	0.59715	<i>R</i>	1×20	1.16	2.44	VLT+FORS2	19.41±0.03
2006 Jun 15.12927	0.59885	<i>R</i>	1×60	1.22	2.41	VLT+FORS2	19.42±0.02
2006 Jun 15.13031	0.59989	<i>R</i>	1×60	1.22	2.39	VLT+FORS2	19.41±0.02
2006 Jun 15.13136	0.60094	<i>R</i>	1×60	2.44	2.37	VLT+FORS2	19.43±0.02
2006 Jun 15.13242	0.60200	<i>R</i>	1×60	2.41	2.35	VLT+FORS2	19.43±0.02
2006 Jun 15.13355	0.60313	<i>R</i>	1×60	2.39	2.33	VLT+FORS2	19.42±0.02
2006 Jun 15.13460	0.60418	<i>R</i>	1×60	2.37	2.31	VLT+FORS2	19.44±0.02
2006 Jun 15.13566	0.60524	<i>R</i>	1×60	2.35	2.29	VLT+FORS2	19.43±0.02
2006 Jun 15.13672	0.60630	<i>R</i>	1×60	2.33	2.27	VLT+FORS2	19.43±0.02
2006 Jun 15.40052	0.87010	<i>R</i>	1×10	2.31	1.16	VLT+FORS2	19.83±0.03
2006 Jun 15.43038	0.89996	<i>R</i>	1×60	2.27	1.22	VLT+FORS2	19.87±0.02
2006 Jun 16.25625	1.72583	<i>R</i>	2×120	1.28	1.22	VLT+FORS1	20.85±0.01
2006 Jun 16.40016	1.86974	<i>R</i>	2×120	1.17	0.45	VLT+FORS1	20.99±0.01
2006 Jun 17.37241	2.84199	<i>R</i>	2×120	1.14	0.50	VLT+FORS1	21.76±0.02
2006 Jun 18.39941	3.86899	<i>R</i>	6×180	1.19	0.65	VLT+FORS1	22.01±0.02
2006 Jun 19.37407	4.84365	<i>R</i>	2×180	1.15	0.50	VLT+FORS1	22.18±0.04
2006 Jun 21.27125	6.74083	<i>R</i>	3×180	1.20	0.60	VLT+FORS1	22.33±0.03
2006 Jun 25.34483	10.81441	<i>R</i>	2×300	1.14	0.90	VLT+FORS1	22.44±0.03
2006 Jun 29.30301	14.77259	<i>R</i>	11×180	1.16	0.50	VLT+FORS1	22.46±0.03
2006 Jul 04.20860	19.67818	<i>R</i>	6×240	1.28	0.60	VLT+FORS1	22.46±0.04
2006 Jul 08.33536	23.80494	<i>R</i>	2×120	1.16	1.40	VLT+FORS1	22.44±0.06
2006 Jul 17.32709	32.79667	<i>R</i>	3×180	1.19	1.10	VLT+FORS1	22.51±0.08
2006 Jul 29.26643	44.73601	<i>R</i>	5×240	1.15	0.90	VLT+FORS1	22.46±0.04
2006 Aug 18.23409	64.70367	<i>R</i>	12×300	1.18	0.60	VLT+FORS1	22.44±0.04
2006 Jun 16.26278	1.73236	<i>I</i>	3×120	1.26	0.55	VLT+FORS1	20.49±0.01
2006 Jun 17.37868	2.84826	<i>I</i>	3×120	1.15	0.43	VLT+FORS1	21.25±0.02
2006 Jun 18.38882	3.85840	<i>I</i>	4×300	1.16	0.75	VLT+FORS1	21.50±0.02
2006 Jul 08.34050	23.81008	<i>I</i>	2×120	1.17	1.10	VLT+FORS1	21.70±0.06
2006 Jul 17.33614	32.80572	<i>I</i>	3×180	1.20	0.95	VLT+FORS1	21.76±0.07
2006 Jun 15.30022	0.76980	<i>J</i>	15×60	1.13	1.20	NTT+Sofi	18.51±0.02
2006 Jun 15.28454	0.75411	<i>K</i>	8×60	1.16	1.15	NTT+Sofi	17.23±0.07
2006 Jun 15.29074	0.76032	<i>K</i>	7×60	1.15	1.15	NTT+Sofi	17.26±0.08
2006 Jun 16.20839	1.67797	<i>K</i>	10×60	1.40	1.10	NTT+Sofi	18.18±0.09