SN 2005ap: A MOST BRILLIANT EXPLOSION

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ABSTRACT

We present unfiltered photometric observations with ROTSE-III and optical spectroscopic follow-up with HET and the Keck telescope of the most luminous supernova yet identified, SN 2005ap. The spectra taken about 3 days before and 6 days after maximum light show narrow emission lines (likely originating in the dwarf host) and absorption lines at a redshift of $z = 0.2832$, which puts the peak unfiltered magnitude at $-22.7 \pm 0.1$ absolute. Broad P Cygni features corresponding to H$\alpha$, C iii, N iii, and O iii are further detected with a photospheric velocity of $\sim 20,000$ km s$^{-1}$. Unlike other highly luminous supernovae such as 2006gy and 2006tf that show slow photometric evolution, the light curve of SN 2005ap indicates a 1–3 week rise to peak followed by a relatively rapid decay. The spectra also lack the distinct emission peaks from moderately broadened (FWHM $\sim 2000$ km s$^{-1}$) Balmer lines seen in SN 2006gy and SN 2006tf. We briefly discuss the origin of the extraordinary luminosity from a strong interaction as may be expected from a pair instability eruption or a GRB-like engine encased in a H/He envelope.

Subject headings: supernovae: individual (SN 2005ap)

Online material: color figures

1.INTRODUCTION

Luminous supernovae (SNe) are most commonly associated with the Type Ia class, which are thought to involve explosions of white dwarf stars; however, the brightest SNe (those with absolute magnitudes $M < -20$) are all associated with the deaths of stars that begin their lives with main-sequence masses $M_{ms} > 7–8 M_{\odot}$. The current record holder, SN 2006gy, is thought to be an explosion of a supermassive star ($M_{ms} \sim 100–150 M_{\odot}$), and it may represent the first detection of a supernova triggered by pair instability (Smith et al. 2007). The remaining bright SNe are attributed to core-collapse induced explosions (CCSNe).

CCSNe are classified as Type Ib/c if they lack strong hydrogen lines in their spectra and Type II otherwise (Filippenko 1997). The latter class has been partitioned into three groups: (1) Type IIn show narrow emission lines in their spectra, (2) Type II-L have linearly declining light curves, and (3) Type II-P are “normal” hydrogen-rich events exhibiting a slow photometric evolution phase (i.e., a plateau). SN 1993J is sometimes classified as a “Type IIb” as its spectral characteristics evolved from Type II-like to resemble a Type Ib, which lack H but show He lines (unlike the Type Ic class). CCSNe may span a continuum with the different spectral types explained in terms of decreasing envelope masses (II-Ib-IIc).

Long-duration gamma-ray bursts (GRBs) are occasionally observed to exhibit SN features. These appear as bumps in the optical afterglow light curves (Bloom et al. 1999; Lazzati et al. 2001) or more revealingly as broad spectral features resembling SNe Ic that emerge in the spectra of afterglows 1–2 weeks after the burst (Stanek et al. 2003). Given the connection of GRBs to SNe Ic and the continuum of CCSNe spectral types, it is natural to consider the observational signature of a GRB engine erupting within an envelope of some mass (e.g., MacFadyen et al. 2001). Such material could slow the ultra-relativistic flow and thus mask the gamma-ray beacon announcing their creation, unlike their stripped progenitor cousins. Young et al. (2005) have explored this possibility and constructed models that can explain the light curves of the bright subclass within the Type II-L group.

In this Letter we report the discovery of SN 2005ap, a transient optical source that peaked at about $-22.7$ mag. We present the photometry in § 2 and the spectral observations and modeling in § 3, and we offer discussion and conclusions in § 4. SN 2005ap is the brightest supernova ever identified and may shed light on energy production mechanisms in cosmic explosions.

2.PHOTOMETRY

SN 2005ap was discovered on unfiltered optical images taken with the 0.45 m ROTSE-IIIb (Robotic Optical Transient Search Experiment) telescope (Akerlof et al. 2003), which is located at the McDonald observatory in west Texas. The transient was found on 2005 March 3 (UT dates are used throughout this Letter) in images taken in the course of the Texas Supernova Search (TSS; Quimby 2006). SN 2005ap was identified in a field centered on the Coma galaxy cluster after removal of static sources via a modified version of the image subtraction code developed by the Supernova Cosmology Project (Perlmutter et al. 1999). SN 2005ap is located at $\alpha = 13^h 01^m 14.83^s$, $\delta = +27^\circ 43^\prime 32.3^\prime\prime$ (J2000.0), which is $6.2^\prime$ projected from SDSS J130115.12+274327.5 (galaxy A in Fig. 1); however, Adami et al. (2006) have cataloged a source $0.6^\prime$ $\pm 0.3^\prime$ west of the transient with $B = 24.6 \pm 0.2$, $V = 23.9 \pm 0.2$, and $R = 23.5 \pm 0.3$, and we identify this as the host of SN 2005ap. SN 2005ap reached an unfiltered magnitude of $18.13 \pm 0.08$ (calibrated against the USNO-B1.0 R2 values) on March 10.28 and was observed at a similar brightness the following two nights (see Fig. 2). The transient was detected over a 40 day period, and it has since remained undetected over two years of observations by the ROTSE-III telescopes (170 nights with limiting magnitudes $18 < M_{lim} < 19.5$). A fourth-order poly-

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1. INTRODUCTION

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A spectrum of SN 2005ap acquired 2005 March 7 with the Low Resolution Spectrograph (LRS; Hill et al. 1998) on the Hobby-Eberly Telescope (HET) shows a very blue continuum with subtle line features including broad absorption and at least one narrow emission line (Fig. 3). Keck LRIS (Oke et al. 1995) data obtained 9 days later exhibit similar behavior and also show narrow absorption lines at wavelengths not covered by the HET. We identify the narrow emission lines observed around 6363 and 6425 Å as [O iii] λ4959, 5007 and a narrow emission line around 8422 Å in the Keck spectrum as Hα. The narrow absorption doublet seen at 3595 Å corresponds to Mg ii λ2796, 2803 in this same frame and sets a firm lower limit for the redshift of SN 2005ap at $z = 0.2832$. At this redshift, the peak unfiltered magnitude is $−22.7 ± 0.1$ absolute ($\Omega_m = 0.265$, $\Omega_\Lambda = 0.735$, $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$). Corrections for minor ($A_v = 0.022$ mag) Galactic extinction (Schlegel et al. 1998) and absorption within the host are not included.

The alignment of the slit for the HET data includes the southern edge of galaxy B, which is 25.7″ from the SN (Fig. 1). These spectra indicate that the redshift of galaxy B is consistent with the Mg ii absorption doublet at 3525 Å ($z \sim 0.26$; projected separation $\sim 100$ kpc). The remaining Mg ii absorption system is consistent with the Sloan Digital Sky Survey (SDSS) photometric redshift of galaxy C in Figure 1, to within the uncertainty (Adelman-McCarthy et al. 2007).

A second observation was conducted with the HET on 2007 February 23, long after the transient had faded below the detection limit of ROTSE-III. The slit was aligned to include the position of SN 2005ap as well as galaxy A. The [O iii] λ4959, 5007 doublet is clearly detected near the location of the transient (Fig. 4). This may indicate that the narrow emission lines are not directly associated with SN 2005ap but rather are intrinsic to the faint host, which has an absolute magnitude,
4. DISCUSSION AND CONCLUSIONS

We have presented photometric and spectroscopic observations of the Type II supernova SN 2005ap. Narrow absorption and emission lines from within the dwarf host indicate a redshift of $z = 0.283$. The successful SYNOW fits and the lack of additional narrow absorption systems indicate that the SN cannot be far beyond this redshift. Correcting only for distance, the peak unfiltered magnitude was $-22.7 \pm 0.1$ absolute, which corresponds to $\sim 4 \times 10^{48}$ ergs s$^{-1}$ assuming no bolometric correction. We consider below the possibility that SN 2005ap was an AGN or a GRB afterglow, but we find it is most consistent with a supernova explosion. We conclude that SN 2005ap is the most luminous supernova ever identified, and roughly twice as bright as the previous record holder, SN 2006gy.

Although the peak absolute magnitude of SN 2005ap is comfortably in the range $-21 > M > -23$ typical of X-ray–selected AGNs around this redshift (Anderson et al. 2007), this interpretation is unlikely. First and foremost, this transient occurred in a region of the sky that has been exceptionally well observed across the electromagnetic spectrum for decades; no indication of a possible AGN at this position has previously been uncovered. Specifically, there are no X-ray detections identified in either the ROSAT All-Sky Survey source catalogs (Voges et al. 1999) or the XMM-Newton Serendipitous Source Catalog, nor is there a cataloged radio source present in either the NRAO VLA Sky Survey (Condon et al. 1998) or the FIRST survey catalog (White et al. 1997). Second, the spectra are quite different from normal AGNs, showing no H$\beta$ or Mg II emission features. There is some similarity to the featureless spectra of certain blazars, although blazars lack P Cygni line profiles and often show narrow lines from giant elliptical hosts (Wurtz et al. 1996). Third, the best position for SN 2005ap is offset from its host at the $2\sigma$ level, and at peak the transient was more than 5 mag brighter than the underlying host light. Finally, no repeat outbursts have been detected at this location in two years of monitoring.

The host galaxy is reminiscent of settings for long-duration GRBs (Fruchter et al. 2006); however, the observed population of GRB afterglows typically decline as power laws ($f \propto t^{-\alpha}$ with $\alpha \sim -1$), and the 1–3 week rise and slow fading of SN 2005ap are inconsistent with this trend. An off-axis orphan afterglow is an interesting possibility, although current models predict a rapid power-law decline after maximum light with $\alpha \sim -1.5$ (Nakar & Piran 2003), which does not appear to match the observations.

Except for its unusually bright peak magnitude, the observations of SN 2005ap are quite consistent with the typical behavior of supernovae. The timescales for the photometric evolution are common among SNe, as is the presence of broad, P Cygni profiles in the spectra. There have been SNe with continuum slopes about as blue as SN 2005ap (e.g., SN 1998S; Fassia et al. 2001), but the existence of C IV, N III, and O III features is unprecedented. The broad H$\alpha$ P Cygni profile is of course the defining feature of SNe II. With no narrow emission lines clearly associated with the explosion and lacking an observed photometric plateau phase, SN 2005ap could be classified as a Type II-L. The light curve is similar in shape to the behavior of SNe II-L (Fig. 2) although it is 3–4 mag too bright. The spectra are also roughly similar to the early observations of SN 1979C (Branch et al. 1981), except SN 2005ap shows a much bluer continuum. However, SNe II-L show broad, asymmetric H$\alpha$ emission with little to no blueshifted absorption, and they also have H$\beta$, H$\gamma$, and He I/Na I P Cygni profiles. These characteristics are wanting in the observations of SN 2005ap. While most SNe II-L have narrowly distributed peak magnitudes, a small subsample (including SN 1979C) deviate to brighter values (Gaskell 1992).

\footnote{Vizier Online Data Catalog, 9029 (W. Voges et al., 2000).}
\footnote{See http://xcatdb.u-strasbg.fr/xcatdb-corr/.}
suggested that these deviants are powered by a GRB engine within a H/He envelope.

The luminosity of normal SNe II is powered by energy deposited by the explosion shock, but this requires that the initial radius of the progenitor be significant compared to the radius of the photosphere in order to minimize adiabatic losses. For an exceptionally bright object like SN 2005ap, this would require an unrealistically large radius. With a photosphere moving at about $v_{\text{ph}} \sim 20,000$ km s$^{-1}$ and a time of maximum light of $t_{\text{max}} \sim 1 \times 10^5$ s, the radius of the photosphere near maximum light is $R_{\text{ph}} \sim 2 \times 10^{15}$ cm, which is much too large to correspond to a standard red supergiant.

If the luminosity arises in the collision of the ejecta with a surrounding, perhaps dense, shell of circumstellar matter shed by a wind or a process like an LBV mass ejection, then we might see the radiation emitted by a shocked, thermalized, shell. For a shell of mass $M_{\text{sh}}$, radius $R$, thickness $\Delta R$, and optical depth, $\tau$, maximum light will occur when the diffusion time, $t_{\text{diff}} \sim 3\Delta R c/\tau$, is comparable to the dynamical time, $t_{\text{dyn}} \sim \Delta R v_{\text{ph}}$. This gives the optical depth at maximum light, $\tau_{\text{max}} \sim \frac{1}{3}(c/v_{\text{ph}}) \sim 5$ neglecting any differences between the photospheric velocity and the mean ejecta velocity. Since $M_{\text{sh}} \sim 4\pi R^2 \tau_{\text{max}}/\kappa$, the mass of the shell would be about $1.3 M_{\odot}$, with $\kappa = 0.2$ for electron scattering. The peak luminosity would be $L \sim \frac{1}{3} M_{\text{sh}} v_{\text{ph}}^2/\tau_{\text{max}} \sim 2 \times 10^{45}$ ergs s$^{-1}$, more than directly observed, but roughly consistent with the observations. The model for SNe II-L by Young et al. (2005) is a variation on this theme, but with the optical luminosity produced by nonthermal emission from the afterglow process.

Another possibility is that a separate internal source of energy powers the luminosity. A model driven purely by radioactive decay would require a large asymmetry to prevent the nickel mass (tens of $M_{\odot}$) from exceeding the ejecta mass (Höflich et al. 1999), which must be modest to account for the rapid rise and decline of the light curve. Whether this could be accomplished with a large nickel mass suggesting a pair formation event, or with a lower nickel mass more commensurate with a “normal” core collapse explosion requires more extended analysis.

Maeda et al. (2007) propose the rapid spin-down of a magnetar to produce a high intrinsic luminosity and subsequent decline from the second peak of SN 2005bf. It is possible that an appropriate choice of (ad hoc) parameters could produce the peak we observe in SN 2005ap, but with a smaller mass and larger temporal decay index to account for the brighter, faster peak.

In two years of operation, the Texas Supernova Search has uncovered the most luminous supernova (this work), the second most luminous (SN 2006gy; Smith et al. 2007; Ofek et al. 2007), and a third, highly luminous event (SN 2006tf; Quimby et al. 2007). The volume monitored over this time (roughly matching the total from all past narrow-field CCD surveys targeting known galaxies), the high completeness of the sample resulting from a tight (nightly) cadence and ability to work in the cores of galaxies, along with prompt high S/N spectroscopic follow-up, have been key to finding and fully classifying these events. The lack of SN 2005ap-like events reported in previous surveys may suggest that they are intrinsically rare, but the lack of SN 2006gy-like events might be understood if they are preferentially located in the cores of bright galaxies. Our discovery of new classes of bright transients bodes well for more extensive future surveys of the time-variable sky.

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REFERENCES

Adami, C., et al. 2006, A&A, 451, 1159
Adelman-McCarthy, J. K., et al. 2007, ApJS, 172, 634
Akerlof, C. W., et al. 2003, PASP, 115, 132
Anderson, S. F., et al. 2007, AJ, 133, 313
Barbon, R., Ciatti, F., & Rosino, L. 1982, A&A, 116, 35
Bloom, J. S., et al. 1999, Nature, 401, 453
Branch, D., et al. 1981, ApJ, 244, 780
Buta, R. J. 1982, PASP, 94, 578
Condon, J. J., et al. 1998, AJ, 115, 1693
Fassia, A., et al. 2001, MNRAS, 325, 907
Filippenko, A. V. 1997, ARA&A, 35, 309
Fruchter, A. S., et al. 2006, Nature, 441, 463
Gaskell, C. M. 1992, ApJ, 389, L17
Hill, G. J., et al. 1998, Proc. SPIE, 3355, 375
Höflich, P., Wheeler, J. C., & Wang, L. 1999, ApJ, 521, 179
Jeffery, D. J., & Branch, D. 1990, in Jerusalem Winter School for Theoretical Physics: Supernovae, ed. J. C. Wheeler, T. Piran, & S. Weinberg (Singapore: World Scientific), 149
Lazzati, D., et al. 2001, A&A, 378, 996
MacFadyen, A. I., Woosley, S. E., & Heger, A. 2001, ApJ, 550, 410
Maeda, K., et al. 2007, preprint (arXiv:0705.2713)
Nakar, E., & Piran, T. 2003, NewA, 8, 141
Ofek, E. O., et al. 2007, ApJ, 659, L13
Oke, J. B., et al. 1995, PASP, 107, 375
Perlmutter, S., et al. 1999, ApJ, 517, 565
Quimby, R. M. 2006, Ph.D. thesis, Univ. Texas
Quimby, R., Castro, F., & Mondol, P. 2007, IAU Circ., 8790, 2
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Smith, N., et al. 2007, ApJ, 666, 1116
Stanek, K. Z., et al. 2003, ApJ, 591, L17
Voges, W., et al. 1999, A&A, 349, 389
White, R. L., Becker, R. H., Helfand, D. J., & Gregg, M. D. 1997, ApJ, 475, 479
Wurtz, R., Stocke, J. T., & Yee, H. K. C. 1996, ApJS, 103, 109
Young, T. R., Smith, D., & Johnson, T. A. 2005, ApJ, 625, L87

References