Early Virtual Science: some lessons for the AVO

Gerry Gilmore

Institute of Astronomy, Madingley Rd, Cambridge CB3 0HA, UK

Abstract. Experience with ASTROVIRTEL, scientific analysis of current large data sets, and detailed preparation for the truly huge future missions especially GAIA, provide important lessons for the Astrophysical Virtual Observatory. They demonstrate that the science cases are impressive, specifically allowing new thresholds to be crossed. The AVO is more than just faster cheaper better, it allows the new. The example of use of pre-explosion imaging of supernova to identify progenitors is used to illustrate some general challenges. Some non-trivial technical astronomical issues arise, especially astrometry, to complement the many technical implementation challenges. A critical scientific lesson is the need to quantify data quality. How are we to ensure the Virtual Observatory produces top science, and avoids being overwhelmed with mediocre data?

1 Introduction

The Astrophysical Virtual Observatory has an exceptionally strong science case. One example, identification of the pre-explosion state of core-collapse supernovae, is described below. This case illustrates some of the technical and strategic challenges which the Virtual Observatory projects have still to face.

There is a strong scientific case to identify and access appropriate archival data on the sites of supernova explosions. Since the candidate star is identified by its self-immolation, the only relevant data are archival! A project to obtain suitable new data to act as a future archive is underway with HST. In addition, much valuable data already exists. Some of this is in archives, and is well calibrated. Much is in private hands. The effort needed to use even excellent quality calibrated and published data is illustrated below, using as examples the searches by Smartt et al for the progenitors of SN1999em and SN2002ap.

One the most difficult of the astronomical challenges facing the integrated use of federated multi-wavelength multi-resolution archives involves source extraction, and astrometric cross-matching. Some examples are given below. The challenge is however obvious to all who have experience even with combination of HST WFPC2 and NICMOS images. Even in this case, with high-quality, high spatial resolution, stable, well-calibrated data sets, with only a one-half decade wavelength range, simple matching of optical and near-IR images of star clusters is not trivial. A nice example is available in figures one and two of Johnson et al (2001), who present PC and NICMOS images of two young LMC globular clusters.

A second challenge involves data reliability. The example below illustrates how even unusually high-quality data cannot be used beyond the range in which
their systematic uncertainties become relevant to the science at hand. However, few (if any) data archives are calibrated well enough to provide this information, except in response to very specific questions and applications.

This raises the spectre of well-meaning providers of what are in fact data of limited calibration ensuring that virtual observatory data product users either produce defective science, or are overwhelmed with learning the limits of every individual data set accessed by the entire system. Might it be that data-archives need a quality-assessment check before they are ‘eligible’ for access? Or is it to be *caveat emptor*?

2 An Example Application: Identifying the progenitors of Type II supernovae

Supernovae are the evolutionary end points of all stars more massive than about $8M_\odot$. Predictions of the pre-explosion evolutionary status of these stars is a key test of stellar evolutionary theory. Supernova explosions additionally drive the chemical evolution of the Universe and play a major role in shaping the dynamics of the interstellar medium of gas rich galaxies. They are of crucial importance to fundamental studies of the evolution of galaxies and the origins of the chemical elements in the Universe.

The spectra of supernovae come in many different varieties, with the classifications based on the lines observed and the temporal evolution of these features. The presence of broad H i optical lines indicates a SN Type II classification, while those that do not show hydrogen are classed Type I. The SNe Ia are thought to arise through thermonuclear explosions in white dwarf binary systems, hence the progenitors are low-intermediate mass stars. All other supernovae including the Types Ib/Ic and all flavours of Type II are thought to be due to core-collapse during the deaths of massive stars. SNe II show prominent, broad H i lines in their optical spectra, indicating that the progenitor retained a substantial hydrogen envelope prior to explosion. SNe Ib/Ic do not show any significant signs of hydrogen in their spectra, although SNe Ib display pronounced He i absorption.

There is strong though indirect evidence that SNe II and SNe Ib/Ic are associated with the deaths of massive stars, as they are never seen in elliptical galaxies, are observed only rarely in S0 galaxies, and they often appear to be associated with sites of recent massive-star formation, such as H II regions and OB associations in spiral and irregular galaxies \[23,5\]. The Type II events are further seen to be split into subtypes (IIb, IIn, II-L and II-P). Leonard et al \[9\] discuss the widely held belief that core-collapse events can be ranked in order of their increasing hydrogen envelope mass at the time of explosion, which is - Ic, Ib, IIb, IIn, II-L, II-P.

This overwhelming, but still indirect, evidence implies that SNe II arise from the deaths of single, massive stars, with initial masses $M > 8 - 10M_\odot$, which have retained a substantial fraction of their hydrogen envelope. However there has been only one definite and unambiguous detection of a star that has subsequently exploded as a supernova of any type — that of Sk$-69^\circ$202, the progenitor to
SN1987A in the LMC \cite{25}. Prior to explosion this star was a blue supergiant of B3 Ia spectral type \cite{24}, which would correspond to $T_{\text{eff}} = 18000$ K (from the temperatures in \cite{11}) and $\log L/L_{\odot} = 5.1$ (from the photometry in \cite{24}), and an initial mass of $\sim 20 M_{\odot}$. The closest supernova to the Milky Way since then was SN1993J in M81 (3.63 Mpc), which was a Type IIb event. Ground based $UBVRI$ photometry of the SN site before explosion was presented by Aldering et al.\cite{1}. The photometry of the progenitor candidate was best fit with a composite spectral energy distribution of a K0 Ia star and some excess $UB$-band flux suspected to be from unresolved OB association contamination (confirmed by recent HST observations). Neither the progenitor of SN1987A nor that of SN1993J is consistent with the canonical stellar evolution picture, where core carbon burning finishes and core-collapse occurs relatively soon afterwards ($\sim 10^3 - 10^4$ yrs) while the massive star is an M-supergiant.

Other attempts have been made to identify SNae progenitors on pre-explosion archive images, with little success in directly detecting progenitor stars. Fortunately, even an upper limit on progenitor brightness provides a mass-limit. An upper mass limit to the progenitor of SN1980K has been estimated to be $\sim 18 M_{\odot}$ \cite{22}, while only an upper limit to the absolute visual magnitude was determined for SN1994I \cite{3}. Recently we \cite{16} studied HST archive images of the site of the Type II-P SN1999gi which were taken before explosion. SN1999gi occurred in a young OB-association: however the the progenitor was below the detection limit of the available pre-explosion images. By determining the sensitivity of these exposures and comparing the estimated bolometric luminosity with stellar evolutionary theory, an upper limit to the mass of the progenitor was set at $9^{+3}_{-2} M_{\odot}$.

3 SN1999em: archival experience with excellent published data

SN1999em in NGC1637 was discovered on Oct. 29 1999 by the Lick Observatory Supernova Search \cite{10} at an unfiltered CCD magnitude of $\sim 13.5^m$. It was soon confirmed to be a Type II and being a very bright event it has been studied extensively in the optical since then. It has been firmly established as a normal Type II-P event, having a plateau phase lasting approximately 90 days after discovery \cite{9}. There have also been UV, X-ray, radio, and spectropolarimetry observations. \cite{2} have presented model atmosphere fits to the early-time optical and HST-UV spectra, indicating that an enhanced He abundance is required to fit the data satisfactorily. They further use the very blue continuum of the early spectrum to determine a reddening. The expanding photosphere method (EPM) has been applied to SN1999em by Hamuy et al.\cite{7} to determine a distance to the host galaxy of $7.5 \pm 0.5$ Mpc, illustrating the possibility of using SNe II-P as luminous distance indicators. Chandra and radio observations of SN1999em have been used to probe the interaction of the SN ejecta with the circumstellar material, which are consistent with a mass-loss rate of $\sim 2 \times 10^{-6} M_{\odot} \text{yr}^{-1}$ and a slow wind \cite{15}. Given the substantial interest in this bright supernova and
the extensive multi-wavelength observations of the event it is of great interest to have direct information on the progenitor star. Further it would be desirable to have more detections of progenitor stars (as in SN1987A) in order to draw a meaningful physical picture of what causes the different varieties of core-collapse events.

By chance there are optical images of this galaxy taken 7 years before SN1999em occurred in the archive of the Canada France Hawaii Telescope, maintained at the Canadian Astronomy Data Centre. These high-resolution images were taken by Sohn & Davidge, who presented photometry of the luminous supergiant members of the galaxy. Among other results in their paper, a distance of 7.8 ± 1 kpc is derived from the magnitudes of the galaxy’s brightest stars. As SNe Type II are thought to have luminous supergiant progenitors, high quality pre-explosion images of nearby galaxies which resolve the brightest stars could allow direct detection of progenitors, or at least limits to be set on luminosity in the event of a non-detection.

In fact, Sohn & Davidge published photometry of a source coincident with the supernova position. Smartt et al. (2002a) however presented an accurate astrometric determination of the position of SN1999em on the pre-explosion frames. They show that there is no detection of a point source at this position which could be interpreted as the progenitor. The detection limits of the exposures are determined, allowing bolometric luminosity limits and an upper mass limit to be determined for the progenitor star.

This discrepancy between different analyses of the same high-quality data using essentially the same photometric techniques illustrates one of the primary challenges for the Virtual Observatory: even high-quality data are often not suitably calibrated for use in a different application than that for which they were obtained, without considerable interactive analysis by an experienced astronomer.

3.1 The challenges of repeat Data Analysis

The galaxy NGC 1637 was observed on 5th January 1992 on the CFHT with the HRCam, with exposures of 900s, 750s and 600s in V, R, I. The material is publicly available through the CFHT archive at CADC. The reduction, analysis and multi-colour photometry of the bright stellar objects in the field was presented by [hereafter SD98]. Their limiting magnitudes for detection, defined as the magnitude where DAOPHOT predicts errors of ±0.5 or greater, are ~24.9, 24.8, 23.9 in V, R, I respectively. These data hence probe stars brighter than M_v ≃ −4.9, assuming the distance modulus from SD98, and their estimates for average line of sight extinction of A_V = 0.34. The image quality of the archive data are 0.7” FWHM in all three bands. SD98 determined the colours for 435 objects in the frames which are simultaneously detected in all three filters. The CFHT HRCam used a 1024×1024 pixel Ford-Aerospace CCD mounted at prime focus, with 18µm pixels, corresponding to 0.13” on the sky.

http://cadcwww.dao.nrc.ca/cfht/
Fig. 1. (a): The position of SN1999em in NGC1637 in a transformed WHT post-explosion image. In this image the centroid of the SN is saturated but a further short exposure is used to measure it accurately, and is set at (0,0) in all frames. (b) and (c): The region of pre-explosion $V\,R$-band CFHT images. (d): An image with a smooth background removed and all PSFs from single stars subtracted. Sohn & Davidge (1998) catalogue a star with a coordinate of $(0.08''$, $-0.24'')$, and magnitude $V = 23.47$, $R = 23.33$ which is within the astrometric error of the transformation discussed in the text. However on close inspection there is no evidence for a point source at this position in any of the $V\,R\,I$ bands. The two stars at $(1.6, 1.9)$ and $(2.9, 0.2)$ have $V = 23.97$, 23.15 and $V - R = 0.26$, 0.10 respectively. The detection limit is position dependent as the background varies considerably over small scales. This figure is from Smartt, Gilmore, Tout & Hodgkin 2002a.

On 28th November 1999, Smartt et al obtained two $V$-band images of NGC1637 on the William Herschel Telescope on La Palma – 30 days after discovery of SN1999em. The AUX-port camera at Cassegrain was used, which has a $1024^2$ Tektronix detector (ING CCD TEK2) at a plate scale of $0.11''$ pix$^{-1}$. This was
done through the ING service program and two exposures were taken (900s and 10s), during which the seeing was 0.7\arcsec FWHM. The considerable similarities between the cameras, telescope apertures and observing conditions in both cases mean the sensitivities of the pre and post-explosion data are very similar, and substantially ease joint analysis (see Fig 1).

Astrometrically calibrating either of the two frames as they stand onto an absolute reference frame is not possible due to their limited FOV, and the fact that any isolated stars outside the main body of the galaxy which could be used as secondary astrometric standards are saturated in the deep CCD frames. However, given the similarity in the plate scales and the detection limits of the two data sets, Smartt et al were able to perform a simple geometric transformation of the WHT pixel array onto the CFHT array (similar to the method in Smartt et al. 2001a). First of all they identified ten bright, relatively isolated stars in both the WHT 900s V exposure and CFHT V frame, and measured the centroids of the stars on the WHT frame by fitting a model point-spread-function (PSF) to each using standard techniques in DAOPHOT within IRAF, using the pixel coordinates of the 10 stars from the tabulated photometry of SD 98. A spatial transformation function was calculated, which fitted a linear shift, a magnification factor and a rotation angle. Polynomials of various orders were tried to fit the x and y mapping, but the results were no better than the simple scaling formerly described. The transformation function was applied to the WHT 900s frame, and both were trimmed to the common region of overlap (625×560 pixels, as shown in Fig 1. This process left no residual systematic difference in the pixel astrometry between these two datasets. The mean offset in radial positions of the stars in the CFHT and WHT frames is $\delta r = 0.17\arcsec \pm 0.13$.

This astrometric mapping process, already rather more elaborate than could be achieved by even careful use of WCS FITS headers, was further complicated by the wide dynamic range difference between the bright and the faint stars, which exceeds the detector dynamic range. The supernova itself of course was saturated, and so would be rejected from analysis by most pipeline processing systems. Thus a further short-exposure astrometric transfer image was also required. Using the stellar centroid method to check for offsets between the long and short frames proved problematic due to the low counts in stars in the short exposure frame; a significantly longer exposure would have led to saturation of the SN. However some stars in common could be matched, and indicated mean offsets of ($-0.01\arcsec, 0.01\arcsec$).

All these transformations required care and one-off interactive checking.

### 3.2 Re-use of published photometry

The photometry list of SD98 reports the detection of star #66 (hereafter NGC1637-SD66) at (0.08\arcsec, −0.24\arcsec) and the nearest other object is 2.5\arcsec away. Star NGC1637-SD66 is the only candidate for the progenitor in the existing photometry of SD98, at a distance of $\delta r = 0.25\arcsec$ from SN1999em. This does fall within the 1\sigma standard deviation of the differences in positions of the 106 matched stars, and hence is compatible with being coincident with the supernova position.
However on closer inspection this does not appear to be a reliable detection of a stellar-like object. In Fig 1 the region around SN1999em is displayed from the CFHT V and R band images. There is no obvious resolved luminous object from a visual inspection and star NGC1637-SD66 is not apparently obvious (the results for the I-band data are similar). The position of the supernova appears to lie on a faint “ridge” (running diagonally left-right in the figure), and the detection limits of the image are highly position dependent given the variable background. In deriving their final photometric list, SD98 applied a background smoothing technique to recover faint stars against the varying galaxy background. Smartt et al. repeated this method to determine if any sign of a single point source at the SN1999em position appears after background subtraction, following the steps described in [19]. The daophot package was used to fit model PSFs to the brighter stars in the images. These were subtracted from the data and a boxcar median filter of pixel dimension 25×25 (i.e. 5 times the seeing width) was applied to this subtracted image. This was assumed to be indicative of the varying background of the galaxy and was subtracted from the original frame. The PSF fitting routines within daophot were re-run on the resultant frame. The results from this for the V band are shown in Fig 1(d), where the point sources subtract off quite cleanly apart from some objects which are not resolved but are broader than a PSF. Again there is no clearly identifiable point-source at the SN1999em position after the smoothing technique is applied, and no object is visible in the R and I frames either.

Smartt et al. conclude that the progenitor of SN1999em is below the sensitivity limits of the pre-explosion VRI data, and that the star NGC1637-SD66 detected by Sohn & Davidge is a noise fluctuation which survived even their exceptionally careful photometric analysis.

4 SN2002ap: a more complex set of archive data

Supernova 2002ap was discovered by Yoji Hirose on 2002 January 29.4 UT in the spiral galaxy M74 [14]. It was discovered at $V = 14.54$, and at a distance of approximately 7.3 Mpc, may be the closest supernova since SN 1993J in M81 (at 3.6 Mpc). Several observers rapidly obtained spectra, reported that it appeared similar to the peculiar SN 1998bw but caught at an earlier epoch [13], exciting much activity. Later optical spectra of SN 2002ap indicate that it does appear to be a Type Ic, and its optical lightcurve appears to have peaked at approximately $M_V \simeq -17.5$, some 1.7" fainter than SN 1998bw. Two popular theories for the origin of Type Ic supernovae are the core collapse of massive stars when they are in the WR phase, or the core collapse of a massive star in an interacting binary which has had its envelope stripped through mass transfer.
SN2002ap in M74: prediscovery optical images, with $BVR\alpha$ from the KPNO 0.9m and $UI$ from the INT WFC. The location of SN 2002ap is at the centre of each frame, indicated by the orthogonal lines. The SN position is $2.31''\pm0.29''$ away from the nearby bright object detected in $BVRI$ (and marginally seen in $U$) i.e. it is clearly not coincident with this source. This figure is from Smartt et al. 2002b.

The host galaxy, M74, is a large and pretty spiral, which has been much imaged by many telescopes, including HST and Gemini-North. However, the supernova lies *Just Off* the field of view of all these high-quality studies. Archival analysis did identify one set of wide-field optical images of M74 taken before discovery of 2002ap. These images are from the Wide-Field-Camera (WFC) on the Isaac Newton Telescope (INT), La Palma, taken on 2001 July 24 through filters $UBVI$. The exposures were 120s in each of $BVI$ and 180s in $U$. These were taken at the end of a night during the Wide Field Survey programme on Faint Sky Variability [6]. The WFC comprises 4 thinned EEV $4k\times2k$ CCDs, with 13.5$\mu$m ($0.33''$) pixels. Repeat exposures of 120s in $UVI$ were taken on 2002 February 2. The supernova core saturated in these frames, and shorter 2-10s exposures were taken with the telescope guiding continuously between the short and long exposures to determine an accurate position for SN 2002ap.

A second set of images was identified by searching the ADS for published studies of M74 which would indicate the existence of data, even though those data had not been archived. Such a study was identified, using data from the KPNO 0.9m with the Direct Imaging Camera taken on 1993 September 15 & 17. The authors were contacted, the tapes found, and *ad hoc* virtual access turned into real access. The subsequent analysis of these data followed the methodology outlined above, and is detailed by Smartt et al. 2002b. Figure 2 shows the outcome, where yet again no progenitor was detected...

The galaxy M74 has been imaged by HST, Gemini, CFHT and WHT, however the supernova position does not fall on any of these images. All the publicly available archives have been searched for deeper, higher resolution images of M74 but there are no superior images to those shown in figure 2 that include the pre-explosion site of SN 2002ap.

The important lesson for the present is that truly ‘virtual’ data, ie data whose existence can be deduced but which are not even physically in an archive, can prove of considerable science value.

5 Supernova progenitors: the Future Virtual Observatory- real observatory interface

We require data on more progenitors before we can be confident of the origins of the core-collapse SNe sub-types. Prompt and frequent multi-wavelength observations of SNe provide quite detailed information on the explosion and circumstellar material, and by inference on the mass-loss and envelope properties of the progenitor. However having high-quality archive images of SNe sites taken
prior to explosion is the only robust way to set firm limits on the nature of the progenitor stars.

Table 1. Comparison of all information that is currently available from direct observations of the progenitors of core-collapse SN. The metallicity refers to estimates for the progenitor star, in the case of the spiral galaxies from measured abundance gradients and galactocentric radii of the SN. Mass refers to the main-sequence mass of the progenitor.

| SN Type | Mass | Z | Spec. Type |
|---------|------|---|------------|
| 1987A H peculiar | 20M⊙ | 0.5Z⊙ | B3Ia |
| 1980K II-L | < 20M⊙ | 0.5Z⊙ | ? |
| 1993J IIb | 17M⊙ | ~2Z⊙ | K0Ia |
| 1999em II-P | < 12M⊙ | 1–2Z⊙ | M-supergiant ? |
| 1999gi II-P | < 9M⊙ | ~2Z⊙ | M-supergiant ? |
| 2002ap I-c | 25M⊙ | 0.5Z⊙ | WR? binary? |

Observations of nearby spiral and irregular galaxies within ~20 Mpc of the Milky Way allow the massive stellar content to be resolved. Multi-band images from the Hubble Space Telescope of all the face on spirals would be an excellent archive for future use when SNe are discovered. In the worst case this will allow limits to be set on the progenitor masses, as shown here and in Smartt et al. (2001), and should lead, in some cases, to definite identifications of progenitor stars. Already the HST archive contains approximately 120 Sb-Sd galaxies within ~20 Mpc which have observations of useful depth in at least 2 broad-band filters. There are a further 130 Sb-Sd spirals with exposures in 1 broad-band filter. Smartt et al have a Cycle 10 HST project to supplement the latter 130 galaxies with 2 further filters, and observe 120 more late-type spirals in three filters. This should give a total of ~370 Sb-Sd galaxies with HST observations. This number is steadily increasing each year, with data coming from projects with other scientific goals. This is supplemented with high-quality ground-based images from the well maintained archives of the ESO, ING, CFHT (and soon Gemini).

The various initiatives aimed at producing combined virtual observatories have, amongst many other applications, the unique historical aspect which is essential to SNe progenitor searches. One of the first of these (ASTROVIRTEL\footnote{http://www.stecf.org/astrovirtel}) has already allowed us to search multi-telescope archives (HST + ESO telescopes) and use catalogue data as search criteria (e.g. LEDA). Along with some manual searching of the ING and CFHT archives, this suggests there are a further 100 spirals with ground-based observations of the quality presented in figures 1 and 2. Assuming a combined SNe II/IIb/Ic rate of $1.00 \pm 0.4 \text{yr}^{-1} (10^{10} L_B ^{-1})^{-1}$, and that the galaxies in our archive have a mean luminosity $\sim 10^{10} L_B ^{-1}$, then one would expect $\sim 4.7 \pm 2$ core-collapse SNe per year in this sample. As the
field-of-view of the WFPC2 on HST will only cover an average of 50% of the area of the optical disk of spirals between 10-20 Mpc, then an estimate of the number of SNe which will have pre-explosion archive material available is \( \sim 2.4 \pm 2 \) per year. Within a period of 3 – 5 yrs we would hence expect the statistics presented in Table 1 to improve significantly. This is an example of unique science to be done with future Virtual Observatories.

6 Conclusions

Identification and analysis of high-resolution ground-based images of the pre-explosion sites of Type II supernovae provide unique information on the late stages of evolution of massive stars, the chemical evolution of the Universe, and the physics of feedback on galaxy evolution. Examples of the successful application of this method are presented above. From a Virtual Observatory perspective there are some important lessons to be learned:

- Even excellent quality and carefully derived data products (crowded field photometry in the specific example here) can prove unsuitable for purposes different than their original application. The scientific integrity of data retrieved by the Virtual Observatory ‘system’ must still be established by the responsible astronomer.
- A considerable amount of non-archived non-calibrated data exist in private repositories. While in some cases this can be of unique value, the work involved in retrieving, and especially in calibrating, old data suggests this is a worthwhile use of resources only in special cases.
- It is interesting to consider if the point above means that the AVO should restrict itself to accessing only well-described and major public data sets.
- A general challenge is to provide adequate astrometric cross-matching for different datasets. This raises the issue of different spatial resolutions, source dropouts, etc. The examples given here suggest that no complete general solution is feasible, except for imaging data from telescopes with extremely well-quantified optical systems.

References

1. Aldering G., Humphreys R.M., Richmond M., 1994, Astron.J., 107, 662
2. Baron E., et al., 2000, A+A , 545, 444
3. Barth A., Van Dyk S.D., Filippenko A.V., Leibundgut B., Richmond M., 1996, Astron.J., 111, 2047
4. Cappellaro E., Evans R., Turatto M., 1999, A+A , 351, 459
5. Filippenko A.V., 1997, ARAA, 35, 309
6. Groot P., et al., 2002, MNRAS, submitted
7. Hamuy M., et al., 2001, ApJ 558, 615
8. Johnson, RA, Beaulieu, SF, Gilmore, G, Hurley, J, Santiago, B, Tanvir, N, & Elson, RAW, 2001 MNRAS 324 367
9. Leonard D.C., Filippenko A.V., Ardila D.A., Brotherton M.S., 2001, ApJ , 553, 861
10. Li W.D., 1999, IAU Circ. No. 7294
11. McErlean N.D., Lennon D.J., Dufton P.L., 1999, 349, 553
12. McClure R.D., et al. 1989, PASP 101, 1156
13. Meikle P., Lucy L., Smartt S., Leibundgut B., Lundqvist P., IAU Circ., 7811
14. Nakano S., Kushida R., Kushida Y., Li W., IAU Circ., 7810
15. Pooley D., et al., 2002, ApJ 572 932
16. Smartt S.J., Gilmore G.F., Trentham N., Tout C.A., Frayn C.M., 2001, ApJ, 556, L29
17. Smartt S.J., Gilmore G.F., Tout, C.A., & Hodgkin, S.T. 2002a ApJ 565 L89
18. Smartt S.J., Vreeswijk, P., Ramirez-Ruiz, E., Gilmore G.F., Meikle, W.P., Ferguson, A., & Knapen, J. 2002b ApJL 572, L147
19. Sohn Young-Jong, Davidge T.J., 1996, Astron.J. 111, 2280
20. Sohn Young-Jong, David T.J., 1998, Astron.J. 116, 130 (SD98)
21. Stetson P.B., 1987, PASP 99, 191
22. Thompson L.A., 1982, ApJ , 257, L63
23. Van Dyk S.D., Hamuy M., Fillipenko A.V., 1996, Astron.J., 111, 2017
24. Walborn N. et al., 1989, A+A , 219, 229
25. White G.L., Malin D.F., 1987, Nature, 327, 36
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