The distance to the Type IIP SN 2013eq

Elisabeth Gall (QUB/MPA), Rubina Kotak (QUB), Bruno Leibundgut (ESO), Stefan Taubenberger (ESO/MPA), Wolfgang Hillebrandt (MPA), Markus Kromer (Stockholm)

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Extragalactic Distances

Required for a 3D picture of the (local) universe

2MASS Redshift Survey

Legend: Image shows 2MASS galaxies color coded by the 2MRS redshift (Huchra et al 2011); familiar galaxy clusters/supergroups are labeled (numbers in parenthesis represent redshift). Graphic created by T. Jarrett (IPAC/Caltech)
Figure 8. Perspective view of the V8k catalog after correction for incompleteness and represented by three layers of isodensity contours. The region in the vicinity of the Virgo Cluster now appears considerably diminished in importance. The dominant structures are the Great Wall and the Perseus–Pisces chain, with the Pavo–Indus feature of significance.
Extragalactic Distances

- Many different methods
  - Galaxies
    - Mostly statistical
    - Secular evolution, e.g. mergers
    - Baryonic acoustic oscillations
  - Supernovae
    - Excellent distance indicators
    - Three main methods
      - (Standard) luminosity, aka 'standard candle'
      - Expanding photosphere method
      - Angular size of a known feature
Expanding Photosphere Method

• Modification of Baade-Wesselink method for variable stars

• Assumes
  – Sharp photosphere $\rightarrow$ thermal equilibrium
  – Spherical symmetry $\rightarrow$ radial velocity
  – Free expansion
Expanding Photosphere Method

\[ \theta = \frac{R}{D} = \sqrt{\frac{f_\lambda}{\zeta_\lambda^2 \pi B_\lambda(T)}} \; ; \; R = v(t - t_0) + R_0; \; D_A = \frac{v}{\theta}(t - t_0) \]

- R from radial velocity
  - Requires lines formed close to the photosphere
- D from the surface brightness of the black body
  - Deviation from black body due to line opacities
  - Encompassed in the dilution factor \( \zeta^2 \)
Expanding Photosphere Method

- Measures an angular size distance
  - Not important in the local universe
  - Interesting for cosmological applications
  - Mostly for $H_0$

- Cosmology
  - Include time dilation
  - Metric theories of gravity imply
    \[ D_L = (1 + z)^2 D_A \]

<table>
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<tr>
<th>$z$</th>
<th>$\frac{D_L}{D_A}$</th>
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<tr>
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Expanding Photosphere Method

• Principle difficulties
  – Explosion geometry/spherical symmetry
  – Uniform dilution factors?
    • Develop tailored spectra for each supernova
      → Spectral-fitting Expanding Atmosphere Method (SEAM) – see Christian Vogl’s talk on Friday
  – Absorption

• Observational difficulties
  – Multiple epochs
  – Spectroscopy to detect faint lines
  – Photometry
SN 2013eq was likely observed shortly after peak brightness.

The initial decline (e.g. Anderson et al. 2014). Typically the plateau lasts up to 100 d before the light curve drops onto the red.

With the objective of estimating the redshift of the SN, we performed a series of cross correlations using SNID (Supernova Identification Program, Schlafly & Finkbeiner 2011).

For SN 2013eq, the host extinction deduced a value of 0.02 mag. The light curves in SDSS-ri are very close to the maximum in these bands. The light curves initial decline (e.g. Anderson et al. 2014).

The selection of redshift values between 0.0 to 0.1, as a conservative estimate. The selected results span a range of redshifts.

Suggested matches were also Hα and [OIII]λ5007. In the classification spectrum (Mikuz et al. 2013; Tomasella et al. 2014) are publicly available at graspa.oapd.inaf.it.

Normalized flux + constant in erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$.

\[ \text{Normalized flux} = \frac{\text{flux}}{A} \]

\[ A = \frac{10^{19}}{\lambda_{\text{rest}}} \]

\[ \lambda_{\text{rest}} = 10^{-2} \lambda_{\text{obs}} \]

\[ \lambda_{\text{obs}} = \frac{\lambda_{\text{rest}}}{1 + z} \]

\[ z = \frac{\lambda_{\text{obs}} - \lambda_{\text{rest}}}{\lambda_{\text{rest}}} \]

\[ \text{Redshift} = \frac{1}{1 + z} \]

\[ z = 0.042 \]

Gall et al. 2016
SN 2013eq

- Two different dilution factors applied
  - Hamuy et al. 2001 (H01)
  - Dessart & Hillier 2005 (D05)

- Both give a good distance to SN 1999em, e.g. Jones et al. (2009)
Standardizable Candle Method

Introduced by Hamuy & Pinto (2002)

- Normalised luminosity during the plateau phase of SNe IIP
- Normally at 50 days after explosion

Used widely for SNe IIP

- Nugent et al. 2006
- Poznanski et al. 2009
- Olivares et al. 2010
- Maguire et al. 2010
- Polshaw et al. 2015
Standardizable Candle Method

- Straightforward simple method
  - Only few observations required

- Issues
  - Need to know explosion time
    - Often not too obvious from observational data
  - Measurement during a ’faint’ epoch
    - Plateau and not maximum
  - Spectroscopy often difficult
    - Faint phase and faint lines
    - Attempts to use prominent hydrogen lines
Distance to SN 2013eq

- Use EPM and CSM to measure distance to same supernova
- EPM provides explosion date to be used by CSM

<table>
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<th>$\mu$ mag</th>
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<td>18.33 ± 0.03</td>
<td>4961 ± 413</td>
<td>36.10 ± 0.22</td>
<td>166 ± 17</td>
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Figure 1. Evolution of the ring collision from 1994 to 2014 (days 2,270 - 9,975) from a combination of HST B- and R-band images. The brightness of the ring has been reduced by a factor of 20 by applying a mask to the images. This makes it possible to see the morphology of the ring at the same time as the faint ejecta and regions outside. The flux scale is otherwise the same for all panels. Note that the spot seen to the south-west already in the first image is a star. Note also that the color evolves with time, which is consistent with the upper panel in Fig. 2. The size of the field is 2.100 × 1.800. North is up, east is left.

Figure 2. Upper panel: R and B band light curves of the full ring from HST photometry. Middle panel: Light curve in individual emission lines from the shocked ring from spectroscopy with VLT/UVES, using a 0.800 slit. Note the different scales on the vertical axis in the panels and the scaling factors for the B-light curve and the lines. Bottom panel: The same for the narrow Hα, [N II] λ6583 and [O III] λ5007 lines from the un-shocked clumps.

The phase ended ⇐ 8,000 days after the explosion and the hotspots are now fading in our observations that extend to 9,975 days. The flux from the hotspots peaked earliest on the east side of the ring. After the peak they, however, all decay, with the south-east decaying most rapidly. Light curves for the individual spots show that the most rapid fading is now in the southeast (Fig. 3, middle panel). The high-resolution spectroscopy from the UVES allows us to separate the contribution to the light curve from the un-shocked ring (emitting narrow lines) and the shocked hotspots (emitting lines with typical velocities ⇐ 300 km s⁻¹). In the middle panel of Fig. 2 we show the light curves of three different lines from the shocked gas (Hα, [Fe XIV] λ5303 and [O III] λ5007), which all show a similar evolution as the HST light curves. In the lower panel we show the fluxes of the strongest narrow lines from the un-shocked gas (Hα, [N II] λ6583 and [O III] λ5007). Up to ⇐ 7,000 days the unshocked [O III] and Hα lines increase in flux, caused by pre-ionization by the soft X-rays. After this epoch all three lines, however, decline more steeply than the lines from the shocked gas.

From UVES observations of Hα we also find that the shocks are radiative up to at least ⇐ 700 km s⁻¹, and possibly up to ⇐ 1,000 km s⁻¹, depending on the angle of the shocks relative to the line of sight (Gröningsson et al. 2008, Migotto et al., 2015, in prep.). This can be compared to the velocities derived from the proper motions in Sect. 2, where the average was found to be ⇐ 540 km s⁻¹. Although the radial and proper motion velocities are in perpendicular directions, the 43 inclination of the ring results in a similar correction, assuming that the expansion is radial from the explosion centre.

Fransson et al. 2015

Indebetouw et al. 2014

SN 1987A – recent news

Claes Fransson (Stockholm)
Josefin Larsson (Stockholm)
Jason Spyromilio (ESO)
The emission line components

Fransson et al. 2013
Evolution of the inner ejecta

Clear change in morphology at optical wavelengths

Larsson et al. 2013
IR observations

[Si I]/[Fe II] 1.644 μm emission

2005
6816 d

2011
8714 d
3-dimensional picture

Derived from \([\text{Si I}]+[\text{Fe II}]\) 1.644\(\mu\)m emission

Emission in the plane of the equatorial ring

Clumpy distribution

Extending out to \(\sim 4500\) km s\(^{-1}\)

Larsson et al. 2013
Inner ejecta

- Complicated region with emission from
  - Cold dust (mm, ALMA; SiO, CO)
  - Infrared emission lines (μm, SINFONI; He, H₂, Si/Fe)
  - Optical emission lines (nm, HST; H)
- Different spatial distributions

Fransson et al., subm.
Emission outside the ring

Figure 4. Upper panel: HST images of SN 1987 with WFC3 in the F625W filter on days 8,717 (2011-01-05), 9,480 (2013-02-06), and 9,975 (2014-06-15). The middle panel shows the difference images of 2013-2011, 2014-2013 and 2014-2011, respectively. Blue means fainter and red brighter. Inside the ring the asymmetric ejecta of the ejecta can be seen. Note the gradual appearance of several small spots, as well as diuse emission, outside the inner ring in the south-east. New spots can also be seen in the north-east, as well as to the north-west. Note that the two new spots in the north-west do not coincide with the stars labelled in the upper left image. The residuals in the south-east corner of the difference images are due to a saturated star and the radial streak north-west of the ring in the two first difference panels is due to a diraction spike of a star outside the field shown. The lower panels show the narrow band images in the F502N ([O III]), F658N ([N II]) and F645N (continuum) filters. The field size is 3.00 × 2.40.

et al. 1997; Pun et al. 2002; Orlando et al. 2005). The fast decay of the narrow lines from the un-shocked gas can be explained as a result of the non-radiative shocks, which traverse lower density gas, replacing the narrow line emission with soft X-ray emission, in combination with a decreasing emission measure of the pre-shock gas in the clumps.

The range of densities in the un-shocked ring has been estimated to 1 × 10^2 cm^-3 up to 3 × 10^4 cm^-3 (Mattila et al. 2010), while the shock speed from the X-ray imaging is ≈1,820 km s^-1 (Maggi et al. 2012; Helder et al. 2013), coming from shocks propagating in the low-density component of the gas. Assuming that the interaction with the ring started on day 5,600 (Helder et al. 2013), the blast wave has expanded by ≈7 × 10^16 cm up to day 9,975, or ≈10% of the radius of the ring. This is of the same order as the distance of the new hotspots outside the ring. It is therefore conceivable that the new hotspots are a result of either the interaction of the blast wave with very dense clumps embedded in gas with density ≈10^3 cm^-3 outside the ring, and close to the equatorial plane, or pre-ionization by the X-rays. The fact that the main part of the ring has faded most in the south-east, where the majority of the new spots are seen supports the former interpretation.

The time scale for the complete destruction of the ring depends on the mass, geometry and density distribution in the clumps (Pun et al. 2002). The mass estimate for the ring, 5.8 × 10^2 M⊙ (Mattila et al. 2010), only refers to the mass ionized by the initial shock breakout, and the mass of the hotspots and gas outside of the ring could be considerably larger. However, extrapolating the light curves in Fig. 2 shows that the ring should fade away between ≈2020 (based on the individual lines) and ≈2030 (based on the HST light curves). The former estimate is likely to be more reliable, as the lines isolate the emission from the shocked ring component. The hotspots will be gradually destroyed by instabilities and conduction by the hot surrounding gas (Borkowski et al. 1997; Pun et al. 2002; Orlando et al. 2005).

The structure outside the inner ring is complex with a possible hour-glass shape (Sugerman et al. 2005; France et al. 2015), which will now be possible to probe. As the shock progresses beyond the circumstellar ring, it will trace the history of mass loss from the supernova's progenitor, revealing the distribution of gas that is now unseen, and providing useful information to discriminate among different models for the progenitor of SN 1987A.

The lower general density will result in a mainly adiabatic shock wave, except for clumps with densities comparable to the inner ring. However, the new hotspots we found probably only represent a small fraction of the mass outside the ring. We expect SN 1987A will become more thoroughly X-ray dominated as the youngest supernova remnant evolves.
Destruction of the ring

- Ring emission has peaked
- Shock is dissolving the ring between 2020 and 2030
SN 1987A – the supernova that keeps giving

- Asymmetric explosion
- Molecule and dust formation in the inner ejecta
- Ionisation of the inner ejecta (Hα) by the ring emission
- Ring destruction has started