Direct distance measurements to SN 2009ip

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ABSTRACT

We demonstrate the applicability of our new method (the Dense Shell Method or DSM) for the determination of astronomical distances by calculating the distance to SN 2009ip. The distance to this supernova has been accurately determined in the standard approach via the cosmic distance ladder and has been found to be 20.4 Mpc. Our direct method, assuming the most reasonable parameter values, gives a very close result, namely $\approx 20.1 \pm 0.8$ (68 per cent CL) Mpc to SN 2009ip.

Key words: supernovae: individual: SN 2009ip – distance scale.

1 INTRODUCTION

In Blinnikov et al. (2012), we introduced a new method for measuring cosmological distances, which we suggest calling the Dense Shell Method (DSM). The method relies on observations of an expanding dense shell in SN IIn and allows one to determine the linear size of such a shell in absolute units, and hence the distance to it, without addressing the cosmological distance ladder. Using this method, Blinnikov et al. (2012) have calculated the distance to SN 2006gy. But the result suffers from quite a large error due to uncertainty in the interstellar extinction and in the colour temperature. Moreover, a small number of observations of the rising part of the light curve, when the shell is believed not to fragment, also lead to a larger uncertainty in the measurements. In this Letter, we examine the applicability of our method to the case of the SN 2009ip, which exploded again in 2012. We show that the DSM allows one to obtain much more accurate results in this case.

2 DIRECT DISTANCE DETERMINATION BY THE DSM

Supernovae of Type IIn are observed at very large redshifts (Cooke 2008; Cooke et al. 2009; Moriya et al. 2012). Since they do not enter the coasting-free expansion phase, neither expanding photosphere method (Kirshner & Kwan 1974) nor spectra-fitting expanding atmosphere method (SEAM; Baron et al. 2004) techniques are directly applicable. Luminous Blue Variables (LBVs) can eject surface layers several times, filling circumstellar space with expanding clouds of relatively dense matter. The kinetic energy of those ejecta may be substantially lower than that of a genuine supernova (see Heger & Woosley 2002). Narrow lines in the spectra of SN IIn indicate

that the matter of the first ejections had velocities an order of magnitude lower than those of the ordinary supernovae (see Grasberg & Nadezhin 1986).

SN 2009ip has produced several outbursts which have been observed directly. The physical mechanisms of those ejections can be different (Heger & Woosley 2002; Chevalier 2012; Soker & Kashi 2013). The time spans between the outbursts can vary substantially. If the time span is large enough, a cavity can be formed between the star and the locus of the maximum density of the cloud. If an LBV giant surrounded by such a cloud from the primary explosion were to outburst again as a genuine supernova or to produce some other kind of a high-velocity outburst, the new ejected material would have a much higher velocity. So in the first days after the shock breakout, the ejecta would propagate through the surrounding low-density cavity of the cold and transparent cloud. The spectra would contain only broad lines born in the high-velocity ejecta. The ejecta would propagate and collide with high-density cloud layers. As a result of this collision, shock waves would run in both directions from the locus of the collision: forward (into the cloud) and backward (into the ejecta).

Below we will consider only spherically symmetric outbursts. Our calculations show that the velocities of these shocks relative to the ejecta are low. This is a consequence of the mass continuity (see equation 9 in Blinnikov et al. 2012, and discussion). One can consider the two shocks as 'glued together' into a dense shell. Moreover, all the kinetic energy of the matter accreted on to the dense shell is transformed into electromagnetic radiation and escapes the cloud. This is why we call this structure a cold dense shell (hereafter CDS). Nevertheless, the part of the cloud in front of the CDS would be heated up and would shine, producing radiation with narrow spectral lines. For the small optical depth of the heated cloud, CDS may become visible (Chugai et al. 2004; Woosley, Blinnikov & Heger 2007). In this case the observed spectrum would have narrow lines on a broad pedestal. In addition, the matter of the cloud would

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be accumulated in the CDS, gradually breaking it, so that eventually our assumption to relative shock velocities would not be justified anymore. Future studies would need to investigate the stability of the CDS (see van Marle et al. 2010).

Calculations show that under certain conditions the photosphere is close to the CDS and moves together with it (e.g. 2006gy; Woosley et al. 2007; Blinnikov et al. 2012). Assuming the equality of the velocities of the matter and the photosphere, one can find the matter velocity from the broad spectral features that allow measuring the photosphere velocity, v_{ph}. If a CDS has already been formed, the radius of the photosphere changes during the time interval dt, evidently, as d$R_{ph} = v_{ph}$dt. A set of models has been built that satisfactorily describes a number of parameters of the ensuing process, including the time dependence of the flux, the colour temperature, the cloud and ejecta velocities, and the cloud density. All the models contain a free parameter, which is the initial radius of the CDS shell. Thus, they do not correspond to a certain distance to the star. Further on, our DSM algorithm selects those models that have the best fit for a sought-for distance. Below for illustration we will consider only primitive models of the blackbody CDS. Let us assume that observations of the supernova spectrum are frequent enough to determine the variation of the photosphere radius according to the relation d$R_{ph} = v_{ph}$dt for several time moments t_i with dt being the time interval between the measurements. Let $\Delta R_i \equiv \int_{t_0}^{t_i} v_{ph}dt$ be the increase of the radius during a large time interval from the initial moment up to the ith time moment. We denote the initial radius (unknown to us) as R_0, and $R_i \equiv R_0 + \Delta R_i$ for $i = 1, 2, 3, \ldots$.

Then using equation 4 from Blinnikov et al. (2012), we find

$$\zeta_{vi}(R_0 + \Delta R_i)\sqrt{\pi B_v(T_{cvi})} = 10^{0.2A_v} D \sqrt{F_{vi}}, \qquad (1)$$

where ζ_{vi} is the dilution factor, T_{cvi} is the colour temperature, obtained from the spectrum, the function B is the blackbody intensity, F_{vi} is the observed flux and A_v is the extinction in stellar magnitude units. All quantities are defined for the frequency v. And finally, D is an unknown distance to the star.

A proper model would allow calculating a set of ζ_{vi} and T_{cvi} for all observational points. From the measured flux, F_{vi}, and increments of the radius, ΔR_i, we can find, using the least-squares method, the initial radius, R_0, and the combination $a_v \equiv 10^{0.4A_v} D^2$. Instead of frequency v one may use index s labelling one of the broad-band filters. To find the distance, D, we need to know A_s, which can be found from astronomical observations.

As we have noticed in Blinnikov et al. (2012), the values of ζ do not vary too much from model to model and only weakly depend on the photospheric radius. In what follows, we assume that the dilution is absent and thus the correction factor is unity, $\zeta = 1$, which is close to the real values of ζ with an accuracy of about 10 per cent as it was found in our radiation hydro models (Woosley et al. 2007; Moriya et al. 2013) for the growing part of the light curve. Of course, a construction of a realistic, more accurate theory requires building a hydrodynamical model not only for the light curve but also for the spectral line profiles with an account of the dilution and projection effects as it has been done for the recent Cepheid models (Gautschy 1987; Sabbey et al. 1995; Rastorguev & Dambis 2011; Storm et al. 2011; Rastorguev et al. 2012).

3 DISTANCE TO THE SN 2009IP

We took the observational data from Prieto et al. (2013), Mauerhan et al. (2012) and Pastorello et al. (2012), and the web page in Prieto (2012).

SN 2009ip began to brighten rapidly after September 24, possibly due to the interaction of the ejecta with the circumstellar material [see Prieto et al. (2013) and discussion in Mauerhan et al. (2012)]. Unfortunately, starting from September 28 the broad lines have mostly disappeared, possibly due to an increasing opacity of the heated circumstellar matter, so it has become difficult to determine the velocity of the CDS (hereafter 'shell' = CDS).

We have used a short two-day period after September 24, for which the velocity of the shell can be determined. During this period the luminosity is proportional to the square of time (Prieto et al. 2013), which corresponds to the constant expansion velocity and the colour temperature of the photosphere.

The photometric data for SN 2009ip in the R band (Bessell 2005) from all three papers are in good agreement [see footnote 32 in Pastorello et al. (2012)]. We took the first 36 points listed in the table from the web page[1] in Prieto (2012). These points correspond to the days that are of most interest to us.

To estimate the expansion velocity v of the shell we have used the data obtained from the Hα absorption component. During the epoch of a sudden increase in the luminosity of the SN 2009ip (around September 23–24), Pastorello et al. (2012) and Mauerhan et al. (2012) indicate values $v \approx 13\,000$ and $\approx 13\,800$ km s^{-1}, respectively. A full analysis is certainly needed to address a question that has not yet been considered: Are the layers of hydrogen, excited to the third level (which produces Hα), close to the photosphere? We have taken the matter velocity to be equal to $v \approx 13\,400$ km s^{-1}.

We have adopted the extinction of $A_R = 0.051$ mag following Mauerhan et al. (2012). In view of the smallness of this value, $10^{0.2A_R}$ is close to unity. The error in A_R has a minor effect on the output. We have taken 0.001 mag for the error value but have not evaluated the impact of its changes on the final result.

Prieto et al. (2013) obtained the blackbody temperature in two different ways. The first blackbody fit took into account the data from the R and I filters and arrived to the value $T \approx 14\,500$ K. The second fit used the longer wavelength coverage (from the near-UV to V band) and the temperature obtained was $T \approx 19\,200$ K. Prieto et al. (2013) treated the derived values as effective temperatures, but the method of obtaining them corresponded to colour temperatures. In our method these values are used as colour temperatures.

To estimate the confidence interval of the calculated distance we have applied a resampling Monte Carlo (MC) simulation based on these data. We have resampled the values of T, the stellar magnitude m_R, in standard filter R, the reddening A_R and velocity v, each with normal distribution. For some of those quantities we have taken the standard deviations from the available data, or fixed them 'manually' for illustration, if they are not known. For example, since we do not know the error of v and T, we have examined how the variations in their errors affect the response.

For obtaining the confidence intervals for the mean and median distances it was sufficient to make 10^5 MC tests.

Taking the temperature of the first Prieto et al. (2013) estimate as $T \approx 14\,500$ K and the relative errors in v and T equal to 5 per cent, we have obtained both the mean and median distances $D \approx 16.1$ Mpc with a 68 per cent confidence interval ± 0.6 Mpc.

If we artificially increase the relative errors of v, T by a factor of 2, we find the distance $D \approx 15.1$ Mpc with a 68 per cent confidence interval $(-1.1, +1.2)$ Mpc. The result is more sensitive to the error in the temperature.
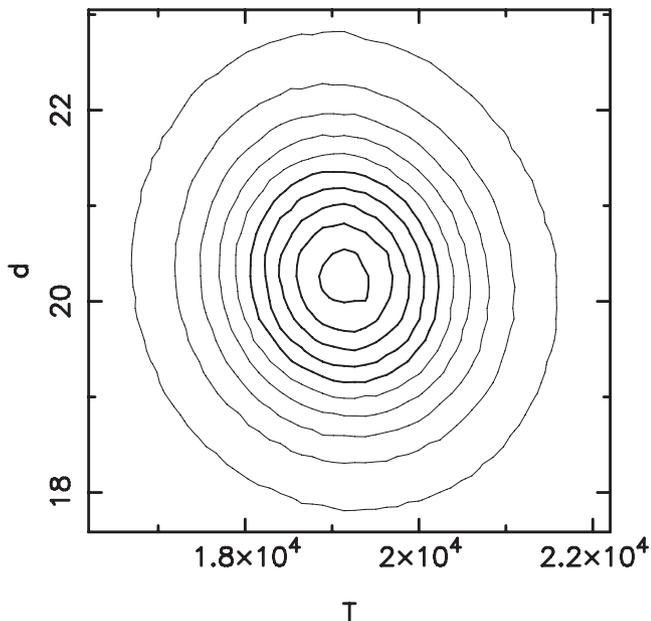
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[1] http://www.astro.princeton.edu/~jprieto/sn09ip/photR.dat

Figure 1. MC resampling simulation of the distance D to SN 2009ip by DSM with respect to temperature T. The isocontours of the probability distribution function (pdf) are shown with equal step in pdf. The observations from Prieto et al. (2013), Mauerhan et al. (2012) and Pastorello et al. (2012) have been used for 36 different time points from the Prieto (2012) web page.

Taking the temperature of the second Prieto et al. (2013) estimate as $T \approx 19\,200$ K and the relative error in v and T equal to 5 per cent, we have obtained the distance $D \approx 20.1$ Mpc with a 68 per cent confidence interval ± 0.8 Mpc. For an illustration of this case, we have built a slice of multidimensional probability density functions on a T–D plane. The plot in Fig. 1 is built with 10^7 samples to obtain better statistics near the top of the distribution. The largest thick-line contour in Fig. 1 is close to one standard deviation.

If we increase the relative errors of v and T by a factor of 2 again, we can find the distance $D \approx 19.9$ Mpc with a 68 per cent confidence interval $(-1.4, +1.5)$ Mpc. The answer is again more sensitive to the error in the temperature. In all the cases the error rise leads to smaller median and mean distances.

These numerical experiments show that the results are rather robust given the level of accuracy of the data and models.

The distance modulus for the galaxy NGC 725, where the SN 2009ip is situated, is generally accepted as $\mu = 31.55$ mag (Smith et al. 2010), which corresponds to 20.4 Mpc. More detailed and complete studies (like SEAM) without the blackbody approximation but with the assistance of a complete hydrodynamical model of the whole sequence of SN 2009ip outbursts permit us to determine the temperature quite accurately. However, we can already say now that in the frameworks of our models, the temperature estimate $T \approx 14\,500$ K is unsatisfactory (if one believes in the generally accepted value of the distance). The goal of the current Letter is not to obtain the most reliable distance value but to show that it can be easily obtained with reliable data. Moreover, increasing the number of observations would reduce the error in the final result as the square root of the number of observations.

Since the host galaxy NGC 725 is relatively close, the Hubble parameter determined only from the redshift measurements can be incorrect because of a large peculiar velocity of the galaxy. On the other hand, the distance to the galaxy NGC 725 calculated with the generally accepted value $H_0 = 71$ km s^{-1} Mpc^{-1} can be significantly different from the distance obtained by other methods. For instance, Levesque et al. (2012) use the distance to NGC 725 equal to 24 Mpc.

The value of the distance is obtained here by a new direct method which does not rely on the cosmic distance ladder! To check the robustness of our results it is necessary to study the effects of variations in correction factors in different SN 2009ip models. We present here the values for the distance only as an illustration of the efficiency of the proposed method.

4 CONCLUSIONS

We have obtained the distance to SN 2009ip equal to $D \approx 20.1 \pm 0.8$ (68 per cent CL) Mpc. The relative error is much smaller than that in the case of SN 2006gy (Blinnikov et al. 2012). If the observations of a supernova are of good quality, and have a large number of data points, the internal error of our method for such a supernova will be very small. A comprehensive application of the method requires a complete supernova SEAM-like model with complex hydrodynamics, taking into account the entire sequence of previous outbursts. One should also evaluate the correction factors (e.g. dilution factor) to eliminate possible systematic errors.

The distance determined in this Letter is calculated under the assumption of the spherically symmetric explosion. The fact that it coincides with the generally accepted value shows that the initial epoch of the growth of the SN 2009ip luminosity is well described with an expanding spherical shell.

Constraining cosmological parameters and understanding the nature of dark energy depend strongly on accurate measurements of distances in the Universe. Our results on SN 2009ip support the conclusion that SNe IIn may be used for cosmology as *primary distance indicators* with the new DSM method.

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