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Determining the distance of type II supernovae

PhD theses

Takáts Katalin

SUPERVISOR:

Dr. Vinkó József

Department of Optics & Quantum Electronics, University of Szeged

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Scientific background

In the last decades supernova (SN) research has become one of the most dynamically developing fields of astronomy. Surveys dedicated to find new transients lead to the discovery of more and more SNe every year, some of which does not fit into any of the known categories. In the meantime, many open questions exist about the classic types, too, about the nature of their progenitors, and the ongoing physical proccesses during and after the explosion. In the first half of my dissertation I review the classification of SNe, and describe the most important properties of each type.

Supernovae play an important role in measuring extragalactic distances. Both type Ia and type II SNe can be used for this purpose. With the help of type Ia SNe the acceleration of the expansion of the Universe has been proven. For this result the Nobel-prize was awarded to Brian Smith, Adam Riess and Saul Perlmutter in 2011. However, the applied methods are based on empirical correlations and – as it was shown by Vinkó et al. (2012b) – the absolute distances provided by different methods still suffer from systematic errors at the 10-15% level.

Type II-P SNe can also be used for distance measurement. There are two possible techniques: the expanding photosphere method (EPM, Kirshner & Kwan, 1974) and the standardized candle method (SCM, Hamuy & Pinto, 2002). The usage of EPM requires photometric and spectroscopic monitoring throughout the plateau phase, starting at a very early phase. The advantage of this method is that it does not need calibration using objects with known distances, it provides independent results. SCM requires less input data than EPM, but it is based on an empirical correlation between the luminosity and the expansion velocity in the middle of the plateau, thus external calibration is necessary.

Both methods rely on the precise measurement of the expansion velocity. Determining its value is not trivial. The usual approach is to measure the Doppler shift of the absorption minima of certain lines. Mostly the Fe II 5169 Å or – at early phases – the Hβ line is used for this purpose. But among others, Dessart & Hillier (2005b) showed that the velocities measured this way can either over- or underestimate the photospheric velocity. The difference is phase-dependent and changes from one supernova to the other.

Several authors (e.g. Poznanski et al., 2009) proposed the application of the crosscorrelation technique. However, this method may lead to high systematic errors when applied for spectra with P Cygni profiles. It might be useful only for spectra having very low signal-to-noise ratio.

The most self-consistent technique to measure photosperic velocity is probably the modeling of the observed spectra with a code that uses radiative transfer and hydrodynamics in non-local termodynamic equilibrium (NLTE). This method, however, requires a large amount of computing power, so its application for a great number of spectra is time-consuming and impractical. This approach was used only for a small sample of SNe so far. There are simpler codes for SN spectrum modeling, such as SYNOW, that use the approximation of local thermodynamic equilibrium (LTE). During my work I examined the applicability of SYNOW for measuring velocities and compared the results to those obtained via other methods.

Research methods

In order to create models of the spectra of supernovae and to measure the expansion velocity I used the parametrized spectrum-modeling code SYNOW, that has been written specifically to model SN spectra (Fisher, 1999; Hatano et al., 1999). This program is based on a few simplifying assumptions: the expansion of the ejecta is homologous, the photosphere radiates as a blackbody, the spectral lines are formed above the photoshere due to pure scattering. The code solves the radiative transfer using the Sobolev approximation.

I selected five type II-P SNe, that have well-sampled, good quality, publicly available data throughout the plateau phase. I created models of their spectra, determined their expansion velocities, and used the results to apply the expanding photosphere method and obtain their distances. With the help of these distances I could also calculate certain physical parameters, using equations that were determined from theoretical models.

Results

1. In order to measure the expansion velocity of type II supernovae I developed an automated method that can be applied for numerous spectra in a much quicker way than previous methods. This method uses the SYNOW code. Changing multiple parameters simultaneously, I created a large number of model spectra, and chose the best-fitting one via χ^2 minimization. In the next step, only the photospheric velocity parameter was modified, the others were kept fixed. In this case the χ^2 minimization was done in the vicinity of a certain line. At early phase the Hβ feature was used, while later, after the appearance of the metallic lines, the ionized iron (Fe II) line, located at 5169 Å rest wavelength was chosen to fit.

   I applied this method for a large number of spectra of five type II-P SNe (SN 1999em, 2004dj, 2004et, 2005cs and 2006bp). I also measured their velocities using other methods. This way I was able to compare the applicability of the different methods, their advantages and disadvantages, as well as the obtained results. *(Takáts & Vinkó, 2012)*

2. I determined the correlations between the velocities measured via SYNOW modeling

and those obtained from the Doppler-shift of certain lines. I established an emirical relation that describes the temporal evolution of the photospheric velocity of type II-P SNe. This equation makes the interpolation of the velocity curve possible, which can be very useful in cases, when there are only a small number of observed spectra or during the application of a distance measurement method which requires contemporaneous photometric- and velocity data. *(Takáts & Vinkó, 2012)*

3. I calculated and refined the distances of the five considered SNe using EPM. The distances obtained from the velocities measured with SYNOW were systematically longer than those that were calculated using the Doppler-velocities of certain lines, while they showed good agreement with the distances of the host galaxies determined via other methods. *(Vinkó et al., 2006; Takáts & Vinkó, 2012)*

4. Using the EPM distance of SN 2005cs I refined the calibration of the standardized candle method. It was necessary because of the lack of a low-energy, low-velocity SN in the previous sample. Taking the new distance into account, I calculated the physical parameters of the explosion. I showed, that these are in good agreement with the ones measured via the direct observation of the progenitor on archive images taken before the explosion. The results show that the progenitor of SN 2005cs was a low-mass ($M_{\rm ZAMS} \approx 9$ $M_\odot$), K3-K4 spectral type supergiant. *(Takáts & Vinkó, 2006)*

5. I determined the photopheric velocities of the type IIb SN 2011dh using the SYNOW models I computed. Combining the data of the SN with those of SN 2005cs that also occured in the same host galaxy, M51, I refined the EPM distance of the galaxy obtaining the value of $D = 8.4 \pm 0.7$ Mpc. The result is in good agreement with the one I calculated for SN 2005cs using the photospheric velocities from SYNOW modeling, but has lower systematic errors. *(Takáts & Vinkó, 2012; Vinkó et al., 2012)*

Publications

Refereed publications associated with the dissertation

- **Takáts, K.**, Vinkó, J.: *Measuring expansion velocities in Type II-P supernovae*, 2012, Monthly Notices of the Royal Astronomical Society, 419, 2783
- Vinkó, J., **Takáts, K.**, Szalai, T. et al.: *Improved distance determination to M 51 from supernovae 2011dh and 2005cs*, 2012, Astronomy & Astrophysics, 540, 93
- **Takáts, K.**, Vinkó, J.: *Distance estimate and progenitor characteristics of SN 2005cs in M51*, 2006, Monthly Notices of the Royal Astronomical Society, 369, 1780
- Vinkó, J., **Takáts, K.**, Sárneczky, K. et al.: *The first year of SN 2004dj in NGC 2403*, 2006, Monthly Notices of the Royal Astronomical Society, 369, 1780

Other refereed publications

- Pastorello, A., Cappellaro, E., Inserra, C., Smartt, S. J., Pignata, G., Benetti, S., Valenti, S., Fraser, M., **Takáts, K.** et al.: *Interacting Supernovae and Supernova Impostors. I. SN 2009ip, is this the end?*, 2012, arXiv: 1210.3568
- Vinkó, J., Sárneczky, K., **Takáts, K.** et al.: *Testing supernovae Ia distance measurement methods with SN 2011fe*, 2012, Astronomy & Astrophysics 546, 12
- Fraser, M., **Takáts, K.**, Pastorello, A. et al.: *On the Progenitor and Early Evolution of the Type II Supernova 2009kr*, 2010, Astrophysical Journal Letters 714, 280
- Vinkó, J., **Takáts, K**: The Expanding Photosphere Method: Progress and Problems, 2007, Supernova 1987A: 20 Years After: Supernovae and Gamma-Ray Bursters. AIP Conference Proceedings, Volume 937, pp. 394-398