Type Ia Supernovae 2014J and 2011fe at the Nebular Phase

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Received July 28, 2015

Abstract—We present our observations and the results of our analysis of the nebular spectra for two nearby type Ia supernovae (SN 2014J and SN 2011fe). For the overall picture, we have analyzed the nebular spectra of four other type Ia supernovae. All of the investigated supernovae show evidence of a significant shift in the [Co III], [Fe III], [Fe II], and [Ni II] lines (∼10³ km s⁻¹) at a late nebular phase (t ∼ 250–300 days). The shifts in the lines of singly and doubly ionized species differ noticeably, suggesting a difference of the departures from symmetry in the inner and outer ejecta. In SN 2014J, the [Fe III] and [Fe II] line shifts are comparable in absolute value and opposite in sign. This means that the shift in the centroid of the ⁵⁶Ni distribution is probably small compared to the width of the velocity distribution. The [Ni II]/[Fe II] flux ratio for the six supernovae suggests that, on average, the ⁵⁸Ni/⁵⁶Fe ratio for SNe Ia is nearly solar, in agreement with the dominant contribution of SNe Ia to the galactic synthesis of iron-peak elements. The nebular spectra of SN 2014J and SN 2011fe are shown to rule out the presence of stripped hydrogen from the normal companion in the amount predicted by the scenario of a binary system with a normal companion.

DOI: 10.1134/S1063773715120014

Keywords: supernovae, nucleosynthesis.

1. INTRODUCTION

Type Ia supernovae (SNe Ia) are known to be produced by the explosions of carbon–oxygen white dwarfs, but the details of the preceding events and the explosion physics itself are not quite clear. Two main origins of SNe Ia are considered: the double-degenerate (DD) scenario—the explosion due to the merging of two degenerate CO dwarfs (Iben and Tutukov 1984; Webbink 1984)—and the single-degenerate (SD) scenario—the explosion of an accreting Chandrasekhar-mass CO dwarf in a binary system with a normal star (Whelan and Iben 1973). Despite the incompleteness of the theory of SNe Ia, some observational consequences of both scenarios are accessible to an observational check. In particular, the SD scenario predicts two important effects of the interaction of SN ejecta with a normal companion: the emission of the material stripped by the SN from the companion in a narrow Hα line (Chugai 1986; Livne et al. 1992; Marietta et al. 2000; Liu et al. 2012) and the early ultraviolet pulse generated by the hydrodynamic interaction of SN ejecta with a normal star (Kasen 2010). Probably, such an effect has recently been observed in the peculiar SN Ia iPTF14atg (Cao et al. 2015) and the normal SN 2012cg (Marion et al. 2015).

3D hydrodynamics simulations of an explosion in the SD scenario predict a nearly spherical expansion. However, significant deviations of the distribution of elements from the spherically symmetric one and even the centrally symmetric one due to noncentral ignition and large-scale convection at the subsonic burning phase are possible in this case (Seitenzahl et al. 2013). The DD scenario predicts a nonspherical structure of the SN ejecta. However, the result depends on the dwarf merging phase at which the explosion occurs: at the time of contact between the merging dwarfs (Pakmor et al. 2012; Moll et al. 2014) or later, when the less massive tidally disrupted dwarf...
has time to form a dense disk around the more massive dwarf before explosion (Raskin et al. 2014). In the former case, a noticeable departure not only from spherical symmetry but also from axial one is expected, while in the latter case, axial symmetry is retained, the departures from spherical symmetry can be significant. In this case, simulations predict a dumbbell structure of the $^{56}\text{Ni}$ distribution resembling a dumbbell (Raskin et al. 2014).

The spectra of SNe Ia at the nebular phase ($t>100$ days) with a high signal-to-noise ratio are an efficient means of searching for evidence of stripped hydrogen and asymmetry in the ejecta. In this period, the ejecta are optically thin in continuum. Therefore, by analyzing the emission bands, one can get an idea of the distribution of emission sources on the line of sight, which, of course, will depend on the orientation of the nonspherical ejecta relative to the line of sight. Analysis of the nebular spectra for SNe Ia in recent years has revealed no evidence of stripped hydrogen but, at the same time, has shown evidence of asymmetry in many cases, with the main one being the shift of the emission line centers relative to the SN rest frame by $\sim10^3 \text{ km s}^{-1}$ (Motohara et al. 2006; Maeda et al. 2010a). A bimodal structure of the line profiles is observed in several cases (Dong et al. 2014).

In this paper, we analyze the spectra of two nearby SNe Ia, SN 2014J in the galaxy M 82 and SN 2011fe in M 101, taken at the nebular phase with the RTT-150 telescope. SN 2014J is of particular interest, because this is the only SN Ia from which the gamma-ray lines at 847 and 1238 keV due to $^{56}$Co decay were detected (Churazov et al. 2014). The question of asymmetry is especially important for this SN, because the approximation of spherical symmetry is used in interpreting the observations of the gamma-ray lines. The search for asymmetry in the [Co III], [Fe II], [Ni II], and [Fe III] emission bands in the spectra of both SNe will be the focus of our attention. For the overall picture, we will also consider the nebular spectra of four more SNe Ia using data from the SUSPECT archive. We will investigate the [Fe II]/[Ni II] 7200 Å blend in the six SNe to find the asymmetry effects and to estimate the relative abundance of the stable isotope $^{58}$Ni. The distribution and synthesis of this element are interesting in that it is an indicator of burning processes in the central dense zone in the deflagration regime (Nomoto et al. 1984).

### 2. OBSERVATIONS

The observations of SN 2011fe and SN 2014J were performed within the time quota of the Kazan University at the 1.5-m Russian-Turkish telescope RTT-150 (Aslan et al. 2001) using the medium- and low-resolution TFOSK spectrograph. A log of observations is given in Table 1. A prism in combination with a 100-$\mu$m (1.8 arcsec) entrance slit and a 2080-pixel CCD array provide a spectral resolution of 15 Å in the wavelength range 4000–9000 Å. The wavelength scale was calibrated using the comparison spectra of a FeAr lamp. To calibrate the fluxes in the spectra, we observed the spectrophotometric standards BD+75d325 and Feige 34. The observed spectral energy distribution of SN 2014J was corrected for interstellar reddening in the galaxy M 82 with $E(B-V) = 1$. The spectra were reduced using a modified version of the DECH software package (www.gazinur.com). The wavelength calibration accuracy is 0.1 Å (5 km s$^{-1}$). An additional uncertainty of $\approx50$ km s$^{-1}$ was caused by the stellar image motions perpendicularly to the spectrograph entrance slit during the exposure. To increase the signal-to-noise ratio in the spectrum of SN 2014J at a late nebular phase, we averaged the spectra taken on November 11 and December 4 and 14, 2014. The average spectrum corresponds to day 303 after maximum brightness.

### Table 1. Log of observations for SN 2011fe and SN 2014J with RTT-150

<table>
<thead>
<tr>
<th>SN</th>
<th>Date</th>
<th>JD</th>
<th>Day after maximum</th>
<th>Exposure, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011fe</td>
<td>Jan. 28, 2012</td>
<td>2455956</td>
<td>+141</td>
<td>3600</td>
</tr>
<tr>
<td>2011fe</td>
<td>Aug. 17, 2012</td>
<td>2456157</td>
<td>+342</td>
<td>5400</td>
</tr>
<tr>
<td>2014J</td>
<td>May 30, 2014</td>
<td>2456809</td>
<td>+119</td>
<td>2400</td>
</tr>
<tr>
<td>2014J</td>
<td>Nov. 11, 2014</td>
<td>2456973</td>
<td>+283</td>
<td>4500</td>
</tr>
<tr>
<td>2014J</td>
<td>Dec. 4, 2014</td>
<td>2456996</td>
<td>+306</td>
<td>5400</td>
</tr>
</tbody>
</table>

Our nebular spectra of SN 2011fe and SN 2014J are presented in Fig. 1 in the SN rest frame. We adopted the recession velocity $v_{hel} = 241$ km s$^{-1}$ for M 101 and $v_{hel} = 111$ km s$^{-1}$ found here (see below) for M 82. While the spectra of both SNe at close phases are generally similar, there are also differences. In particular, the main emission features in SN 2011fe show a blueshift ($\sim10^3$ km s$^{-1}$) relative to SN 2014J. Note that SN 2014J has a substantial reddening due to interstellar dust in M 82. As a consequence, strong interstellar Na I absorption lines falling on the [Co III] 5900 Å emission are present in the spectrum.