The circumstellar matter of supernova 2014J and the core-degenerate scenario

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ABSTRACT
I show that the circumstellar matter (CSM) of the type Ia supernova 2014J is too massive and its momentum too large to be accounted for by any but the core-degenerate (CD) scenario for type Ia supernovae. Assuming the absorbing gas is of CSM origin, the several shells responsible of the absorption potassium lines are accounted for by a mass loss episode from a massive asymptotic giant branch star during a common envelope phase with a white dwarf companion. The time-varying potassium lines can be accounted for by ionization of neutral potassium and the Na-from-dust absorption (NaDA) model. Before explosion some of the potassium resides in the gas phase and some in dust. Weakening in absorption strength is caused by potassium-ionizing radiation of the supernova, while release of atomic potassium from dust increases the absorption. I conclude that if the absorbing gas originated from the progenitor of SN 2014J, then a common envelope phase took place about 15,000 years ago, leading to the merging of the core with the white dwarf companion, i.e., the core-degenerate scenario. Else, the absorbing material is of interstellar medium origin.

Key words: binaries: general supernovae: individual: SN 2014J, supernovae: general,

1 INTRODUCTION

Type Ia supernovae (SN Ia) are thermonuclear explosions of white dwarfs (WDs) accompanied by a complete destruction of the WD, or at least one of the two interacting WDs (e.g. Maoz et al. 2014). There is as of yet no consensus on the scenario that brings a WD or two to explode. In recent years there have been several different scenarios, that were classified into five categories by Tsebrenko & Soker (2015a). We list them below by their alphabetical order, and cite only a limited fraction of the literature on each scenario.

(a) The core-degenerate (CD) scenario (e.g., Sparks & Stecher 1974; Livio & Riess 2003; Kashi & Soker 2011; Soker 2011; Ilkov & Soker 2012, 2013; Soker et al. 2013).

(b) The double degenerate (DD) scenario (e.g., Webbink 1984; Iben & Tutukov 1984; van Kerkwijk et al. 2010; Lorén-Aguilar et al. 2012; Pakmor et al. 2013; Aznar-Siguán et al. 2013).

(c) The double-detonation (DDet) mechanism (e.g., Woosley & Weaver 1994; Livne & Arnett 1995; Shen et al. 2013).

(d) The single degenerate (SD) scenario (e.g., Whelan & Iben 1973; Nomoto 1982; Han & Podsiadlowski 2004).

(e) The WD-WD collision (WWC) scenario (e.g., Raskin et al. 2008; Rosswog et al. 2009; Thompson 2011; Katz & Dong 2013; Kushnir et al. 2013).

As there is no consensus on the SN Ia progenitor(s), it is crucial to refer to all five scenarios (or categories of scenarios) when confronting observations with SN Ia scenarios. In the present study I examine some properties of the type Ia SN 2014J, concentrating on the medium around it. I take into account limits on the pre-explosion progenitor (Kelly et al. 2014; Nielsen et al. 2014) and its mass loss (Pérez-Torres et al. 2014), and the properties of the absorption potassium lines (Ritchey et al. 2014), and their time-variability (Graham et al. 2015).

From radio observations Pérez-Torres et al. (2014) limit the mass loss rate from the progenitor of SN 2014J to \(< 7.0 \times 10^{-10} M_\odot \text{yr}^{-1}\) for a wind speed of 100 km s\(^{-1}\). This contradicts many cases of the SD scenario, but not those with a long delay to explosion (Di Stefano et al. 2011; Justham 2011). Pérez-Torres et al. (2014) consider the DD scenario to be the alternative to the SD scenario; without explanation they ignore the other three scenarios listed above, and the presence of dense circum-stellar matter (CSM) in some cases of the DD scenario (Moll et al. 2014; Raskin et al. 2014; Levanon et al. 2015). A similar but weaker constraint is obtained from X-ray observations by Margutti et al. (2014), who also conduct a thorough discussion of possible scenarios, leaving some room for the SD scenario with time delay to explosion (Di Stefano et al. 2011; Justham 2011) and for the CD scenario. One should note that the WWC scenario also complies with these limits on the close CSM. Graham et al. (2015), on the other hand, attribute the time-varying potassium lines from SN 2014J to a CSM, and argue that their results tentatively support a SD scenario for SN2014J.
In this study I reexamine the claims for a CSM around SN 2014J, and try to reconcile such a CSM with the CD scenario. I do not get into the dispute whether the absorbing material is of CSM (e.g., Foley et al. 2014) or of interstellar medium (ISM) origin (e.g., Johansson et al. 2014), but rather discuss the consequences of the case that the absorbing gas, or some of it, is of CSM origin. In section 2.1 examine the potassium lines, and in section 3 estimate the mass of the absorbing gas based on the results of Graham et al. (2015). Under the assumption that the absorbing material, or part of it, originated from the progenitor of SN 2014J I confront the different scenarios with the CSM properties in section 3.

2 POTASSIUM ABSORPTION LINES

The absorption potassium lines were studied by Ritchev et al. (2014) and Graham et al. (2015). In examining the high-resolution spectrum presented by Graham et al. (2015) in their figure 3, one can notice time variations of absorption lines at three velocities. At velocities of \(v = -144, -127 \text{ km s}^{-1}\), the most blue shifted lines in K I, the absorption lines were weakening with time, while at the velocity of \(-81 \text{ km s}^{-1}\) the absorption line became stronger with time. No time variation was found in any of the sodium lines.

The weakening of the potassium absorption lines can be attributed to the ionization of neutral atoms by the SN radiation. Graham et al. (2015) find that while K I shows time-variation, no such variation is observed in any of the Na I line. For some Na I lines this invaribility is due to their saturation. Graham et al. (2015) argue that if the absorbing material resides at \(0.6 - 1.6 \times 10^{19} \text{ cm} \) from the SN, then the potassium ionization fraction increases substantially with time, while the sodium suffers only a moderate increase in ionization fraction. This can account for the weakening of the \(v = -144 \) and \(-127 \text{ km s}^{-1}\) K I absorption lines.

The observation that only the two most blue-shifted lines show this behavior was attributed by Graham et al. (2015) to these shells being the closest shells to be SN. The other shells in their explanation have been slowed down by the ISM. As I show in the next section, this explanation is problematic, as the implied total mass in the shells in such a mass distribution is larger than \(8M_{\odot}\). This is more than a progenitor of SN Ia can supply.

Graham et al. (2015) do not study the strengthening of the \(-81 \text{ km s}^{-1}\) K I absorption line. The strengthening of absorption lines can be attributed to either the opposite process of recombination, or to the release of more neutral atoms from dust. The process by which the SN Ia radiation releases sodium from dust residing at \(\approx 1 \text{ pc} \) from the SN, the Na-from-dust absorption (NaDA) model (Soker 2014), is similar to the processes by which solar radiation releases sodium from cometary dust when comets approach a distance of \(\lesssim 1 \text{ AU}\) from the Sun. The NaDA model was suggested to account for time-varying sodium lines in SN Ia (for observations of Na I lines in SN Ia see, e.g., Patat et al. 2007; Simon et al. 2009; Sterenberg et al. 2011, 2014; Maguire et al. 2014). Dust in the solar system is known to release potassium in addition to sodium, e.g., Fulle et al. (2013). I here suggest that the deepening of the \(-81 \text{ km s}^{-1}\) absorption line in the spectrum of SN 2014J is a result of potassium release from dust, as in the NaDA model.

The velocity of the line is explained within the CD scenario, if the absorbing gas is indeed a CSM and not an ISM, in the following way. Some or all of the absorbing clouds/shells were ejected by the progenitor within a very short time period, the common envelope (CE) phase of the progenitor binary system. The shells are actually clumpy nebula expanding in a linear relation between distance and velocity. Namely, the \(-81 \text{ km s}^{-1}\) gas is at a distance of \(81/144\) times the distance of the \(-144 \text{ km s}^{-1}\) gas from the explosion. Such expanding clumpy nebulae with a linear distance-velocity relation and expansion velocities of up to few hundreds \(\text{ km s}^{-1}\) is observed in some planetary nebulae (PNe), e.g., NGC 6302 (e.g., Meaburn et al. 2008; Szyzska et al. 2011), and the pre-PN M1-92 (IRAS 19343+2926; Bujarrabal et al. 1998).

My suggestion that the absorbing gas of the most blue-shifted lines lies at the largest distances from the explosion is opposite to the claim of Graham et al. (2015), but gives a lower CSM mass that can be compatible with a CSM, as is shown in the next section. The proposed scenario implies that SN 2014J is a SN-Inside a PN (SNIP, Tsebrenko & Soker 2013 2015).

3 THE MASS OF THE ABSORBING GAS

I first consider the three potassium absorption lines where time-variability is observed (Graham et al. 2015). The column densities of the neutral potassium of the gas absorbing in the \(-144 \text{ km s}^{-1}\), \(-127 \text{ km s}^{-1}\), and \(-81 \text{ km s}^{-1}\) lines are \(0.50 \times 10^{13} \text{ cm}^{-2}\), \(4.0 \times 10^{13} \text{ cm}^{-2}\), and \(1.1 \times 10^{13} \text{ cm}^{-2}\), respectively. Ritchev et al. (2014) Graham et al. (2015) find a somewhat higher column density of \(0.80 \times 10^{14} \text{ cm}^{-2}\) for the \(-144 \text{ km s}^{-1}\) shell. Using higher column densities will strengthen the conclusions reached here.

The mass of a shell, or a partial shell, at a radius \(r_s\) with an atomic potassium column density of \(N(KKI)\) and a solar composition (Asplund et al. 2009) is given by

\[
M_s = 0.53 \left( \frac{N(KKI)}{10^{13} \text{ cm}^{-2}} \right) \left( \frac{r_s}{2 \text{ pc}} \right)^2 \frac{\beta}{\xi} M_{\odot},
\]

where \(4\pi\beta\) is the solid angle covered by the shell and \(\xi^{-1}\) is the fraction of the potassium in the atomic phase. Both \(\beta < 1\) and \(\xi\) are likely to be less than unity.

The scaling of \(r_s = 2 \text{ pc}\) is the minimum radius allows by Graham et al. (2015) in their explanation for the time variation of the two most blue-shifted K I lines. For the values of \(r_s = 2 \text{ pc}\) and \(\beta/\xi = 1\), the masses of the two shells are \(M(-144) = 0.26M_{\odot}\) and \(M(-127) = 2.1M_{\odot}\). If the mass is spread over a radial distance of \(\approx 1 \text{ pc}\), the duration of the mass loss process is \(\approx 1 \text{ pc}/140 \text{ km s}^{-1} \approx 7000 \text{ yr}\). The mass loss rate is \(\approx 2M_{\odot}/7000 \text{ yr} = 3 \times 10^{-4}M_{\odot} \text{ yr}^{-1}\). This is a very high mass loss rate, more than is expected from any model for the SD scenario where a low mass transfer rate is required from a giant to the WD companion. The existence of shells suggests that the mass loss rate was over a shorter time scale than 7000 yr, and mass loss rate was higher even.

As mentioned in section 2 the existence of clumps with a velocity spread is observed in some PNe and pre-PNe, and in some cases with a linear velocity-distance relation. In these cases the mass ejection was a short event, most probably a CE phase, and possibly an intermediate-luminosity optical transients (ILOT) event (Kashi & Soker 2011, Akashi & Soker 2013). A bipolar PN is formed with a solid angle coverage of \(\beta < 1\).

To examine this CD scenario, I do the following exercise. I take the blue-shifted shells listed by Ritchev et al. (2014) to originate from the progenitor of SN 2014J, and obey

\[
\tau = t_{ejc} v_s(i) = 1.53 \left( \frac{t_{ejc}}{1.5 \times 10^4 \text{ yr}} \right) \left( \frac{v_s(i)}{100 \text{ km s}^{-1}} \right) \text{ pc},
\]
where \( r_s(i) \) and \( v_s(i) \) are the radius and the velocity of shell \( i \), and \( t_{ejc} \) is the time since the shells were ejected in a short event by the progenitor of SN 2014J. Equation (2) takes SN 2014J to be in the rest frame of M82. However, SN 2014J is in the approaching side of M82, and it is likely that the relative shells velocities to SN 2014J are somewhat lower. In that case the absorbing gas likelihood to be of ISM origin is higher. In the present study I examine the implications of the absorbing gas being of CSM origin, and take the shells distances from the explosion according to equation (2).

The outer shell has \( v = -144 \text{ km s}^{-1} \) with \( r_s(-144) = 2.2(t_{ejc}/1.5 \times 10^4 \text{ yr}) \text{ pc} \). After summing over all the shells I find the CSM mass in the CD scenario (assuming all blue-shifted shells belong to the CSM) to be

\[
M_{\text{CSM-CD}} = 5.4 \left( \frac{t_{ejc}}{1.5 \times 10^4 \text{ yr}} \right) \frac{\bar{\beta}}{\xi} M_\odot, \tag{3}
\]

where \( \bar{\beta} \) and \( \xi \) are average values for the solid angle covered by the shells and the fraction of potassium in the atomic state; both are expected to be less than unity. The total mass of the three shells that show time-variability with the same scaling is \( 2.2 M_\odot \). Over all, the progenitor had to expel \( \approx 2 - 6 M_\odot \) over a relatively short time of \( \lesssim 10^4 \text{ yr} \). The mass loss rate during the formation of the shells, if they are indeed CSM, was \( \gtrsim 10^{-4} M_\odot \text{ yr}^{-1} \). A single star of mass \( < 8 M_\odot \) is not expected to have such a high mass loss rate. A CE interaction seems the most natural explanation for such a mass loss rate.

Other relevant points to the proposed mass distribution are as follows.

1. If all shells reside outside 2 pc, as suggested by Graham et al. (2015), then the mass with the above scaling is \( > 8 M_\odot \). Larger than what a progenitor of a SN I can supply.

2. Johansson et al. (2014) limit the dust mass within \( \approx 10^{17} \text{ cm} \) from SN 2014J to be \( \lesssim 10^{-5} M_\odot \). The inner shell in the structure discussed above is taken to be the one with a velocity of \(-19 \text{ km s}^{-1}\). Its distance from the center is \( r_s(-19) = 9 \times 10^{17}(t_{ejc}/1.5 \times 10^4 \text{ yr}) \text{ cm} \), and its mass is \( M_s(-19) = 0.004/\xi M_\odot \) under the assumptions employed here. The location and mass of the shell is compatible with the limit set by Johansson et al. (2014). If the mass distribution employed here is correct, then within about two years from the explosion, sometime in 2016, the infrared radiation from warming CSM dust might start to increase.

3. Nielsen et al. (2014) argue that SN 2014J comes from a young population. A mass transfer from the initially massive primary star, \( M_{10} \approx 5 - 8 M_\odot \), to the secondary could leave a massive secondary on the main sequence, \( M_2 \approx 7 - 8 M_\odot \), that expelled such a large mass during the CE phase Ilkov & Sokolov (2013), as in the case of PTF 11kk (Soker et al. 2013). (Note that in PTF 11kk the CSM was much closer to the exploding star.)

4. In this study I do not deal with the question of why three shells show time-variability, but not the others. It might be related to the density of the shells, or some other properties. This might actually be an argument for that the shells are ISM shells, and not CSM shells. However, then one will have to explain why most of the shells show blue-shifted absorption. I do note that even if only the three time-variable shells belong to the CSM, the discussion to come still holds.

4 DISCUSSION AND SUMMARY

In the present study I do not get into the question whether the gas responsible for the potassium absorption lines is of CSM or ISM origin. This question is not settled yet. I consider the implications of the CSM case. Namely, where some, or all, of the absorbing clouds/shells were originated from the progenitor of SN 2014J, as argued most recently by Graham et al. (2015). But one must keep in mind that it is quite possible that all the absorbing gas clouds/shells are ISM. In any case, the discussion in this section is relevant for future observations of CSM around SN 1a, as I confront each of the five scenarios listed in section 3 with the properties of the absorbing gas of SN 2014J if it is of CSM origin.

4.1 The core-degenerate (CD) scenario

In the CD scenario the pre-explosion mass ejection episode in SN 2014J lasted for a relatively short time, at most few hundreds of years, which is the CE evolution time. The distances of the shells from the explosion is more or less their velocity times the time from mass ejection to explosion, as given in equation (2).

The merger of the core with the WD could have energized the shells to the high velocities, up to 140 km s\(^{-1}\), more than the typical velocities of post-CE nebulae, few \( \times 10 \) km s\(^{-1}\). Taking the shells radii used in previous sections (based on Graham et al. 2015), the age of the nebula is \( \approx 1.5 \times 10^4 \text{ yr} \). The evolution of cores of AGB stars with masses of \( \approx 0.6 M_\odot \) is rapid enough that their luminosity and temperature after \( \approx 1.5 \times 10^4 \text{ yr} \) post-AGB evolution are \( L_{\text{ce}} \approx 200 - 250 L_\odot \) and \( T_{\text{ce}} \approx 10^4 K \), respectively, e.g. Bloemen (1995). This luminosity is below the upper limit on the luminosity of the progenitor of SN 2014J of \( \approx 10^5 L_\odot \) (Kelly et al. 2014).

The ejection of the entire envelope explains the large mass of the shells, \( \approx 2 - 6 M_\odot \), found in section 3.

By the post-CE time of \( 1.5 \times 10^4 \text{ yr} \) the wind mass loss rate from the central star is \( \approx 10^{-10} M_\odot \text{ yr}^{-1} \) and its velocity is thousands of \( \text{ km s}^{-1} \) (Schönberner et al. 2014). This gives a very low density gas close to the explosion, \( r < 10^{18} \text{ cm} \), that is safely compatible with the limit set by Pérez-Torres et al. (2014) and Marquetti et al. (2014) on the mass loss rate from the progenitor hundreds of year before explosion.

Despite the hot-luminous central star, most of the material can be stay neutral, as required by the observed absorption. The hydrogen ionizing photon rate per unit solid angle from a post-AGB star with an effective temperature of \( T_{\text{eff}} = 10^4 \text{ K} \) is

\[
\dot{n}_i(10^5 K) = 1.7 \times 10^{45} \left( \frac{L_\odot}{300 L_\odot} \right) \text{ s}^{-1} \text{ sr}^{-1}. \tag{4}
\]

The hydrogen recombination rate of a partial shell covering a solid angle of \( 4\pi\bar{\beta} \), for a gas temperature of \( 10^4 \text{ K} \), and almost fully ionized is

\[
\dot{n}_{\text{rec-}i} = 1.9 \times 10^{45} \beta^{-1} \left( \frac{m_i}{0.3 M_\odot} \right)^2 \times \left( \frac{r_i}{10^{18} \text{ cm}} \right)^{-3} \left( \frac{\Delta r_i}{0.1 r_i} \right)^{-1} \text{ s}^{-1} \text{ sr}^{-1}. \tag{5}
\]

where \( r_i \) is the radius, \( \Delta r_i \) is the thickness, and \( m_i \) is the mass of the ionized shell (or partial shell).

Comparing equations (4) and (5) shows that an inner shell of about 10% of the total shell mass, i.e., \( m_i \approx 0.2 - 0.6 M_\odot \), can shield the outer shells from the pre-explosion ionizing radiation.
This can account for the neutral potassium and sodium phase that is required for the observed absorption.

4.2 The double-degenerate (DD) scenario

The massive shells require a CE evolution. The shells were ejected \( < 2 \times 10^4 \) yr ago, which is the post-CE period. This implies that (a) the core is still very hot during the WD-core merger, and (b) that for about a thousand years the core is still larger than a cold WD, a radius of \( R > 0.1R_{\odot} \). For gravitational radiation to bring the core-WD system to merge within the WD, a radius of \( \approx 0.1R_{\odot} \), at this separation tidal interaction with the larger core would cause the merger rather than gravitational radiation. For these two reasons the CD scenario is a more appropriate description of the evolution than a DD scenario.

4.3 The double-detonation (DDet) scenario

There are two issues here. (1) The time from the formation of a donor He-WD to the mass transfer phase form the He-WD to the WD in the DDet scenario is very long (Shen et al. 2013), much longer than the post-CE evolution of SN 2014J. (2) The expected CSM mass in the DDet scenario is very low, \( \lesssim 1M_{\odot} \) (Shen et al. 2013). For these two reasons the DDet scenario cannot account for the potassium absorbing gas of SN 2014J if it is of CSM origin.

4.4 The single-degenerate (SD) scenario

In the SD scenario there is no strong interaction between the donor star and the WD. The mass loss rate is not expected to be as high as inferred in section \( \dot{M} \gtrsim 3 \times 10^{-4}M_{\odot} \) yr\(^{-1}\). The radial momentum discharge of the shells is defined as the radial momentum of the shells divided by the ejection time. I find this value for the shells, if of CSM origin, to be \( \dot{M} \gtrsim 10^{29} \) g cm s\(^{-2}\). The radiation momentum discharge is \( L_*/c = 1.3 \times 10^{28}(L_*/10^5L_{\odot}) \) g cm s\(^{-2}\). A wind from a single giant star of mass \( < 8M_{\odot} \) cannot explain the momentum in the absorbing shells.

Another problem is the time span between mass ejection and explosion. Since the present luminosity of the companion is limited to \( \lesssim 10^4L_{\odot} \) (Kelly et al. 2014), any companion with such a massive CSM must be brighter on the asymptotic giant branch (AGB). To explain the massive CSM, the giant donor should have lost most of its envelope within \( < 2 \times 10^4 \) yr prior to explosion. In the SD scenario there is no explanation why explosion should occur within this time scale. This is unlike the CD scenario, where the time scale is explained as a post-CE evolution.

4.5 The WD-WD collision (WWC) scenario

In the WWC scenario the two progenitors of the two WDs should have no interaction at all before the final collision. As explained for the SD scenario above, a single AGB star cannot account for the momentum and mass loss rate that formed the shells, if of CSM origin. This adds to the several problems the WWC scenario encounters when compared with observations (Tsebrenko & Soker 2015a), despite the one strong character that the ignition is easy to achieve in the collision process. The most severe problem of the WWC scenario is that it cannot account for more than about one percent of all SN Ia (e.g., Soker et al. 2014; see section 2 in the first astro-ph version of this paper, arXiv:1309.0368v1).

Manganese production is not accounted for in the WWC scenario. Tamagawa et al. (2009) identified X-ray lines from manganese in the Tycho SNR. Seitenzahl et al. (2013) further claim that at least 50% of all SN Ia come from near Chandrasekhar mass (\( M_{\text{Ch}} \)) WDs, as the density required to synthesize manganese is \( \rho \gtrsim 2 \times 10^8 \) g cm\(^{-1}\) (Seitenzahl et al. 2013 and references therein). The WWC scenario does not reach these densities, and cannot account for the production of manganese. The same problem holds for the DDet scenario.

Another problem seems to be the iron distribution in the SN remnant (SNR). Dong et al. (2014) consider the presence of doubly-peaked line profiles of cobalt and iron as a possible smoking gun for the WWC scenario. Although Dong et al. (2014) account for the doubly-peaked lines, it seems that they predicted iron distribution in contradiction with iron distribution of two resolved SNRs. Yamaguchi et al. (2013) present the 2D iron distribution in the SNR of the possible SN Ia G344.7-0.1, and Fesen et al. (2015) present the iron and calcium 2D distributions in the SNR 1885 in the Andromeda galaxy. In both SNRs the iron distribution is clumpy, and does not show two prominent distributions as expected from the WWC scenario.

4.6 Summary

Under the assumption that the gas responsible of the potassium absorption lines in SN 2014J, either only time-variable lines or all lines, is CSM formed by the progenitor of SN 2014J, I found in this study that the CD scenario is the only scenario that can account for the mass and momentum of the absorbing gas.

This does not mean that the issue is completely settled. There are several open questions in the CD scenario that still need to be worked out. Specifically for SN 2014J the time-variability of three absorption lines and invariability of the other lines should be explained. More generally, the processes of the core-WD merger, the evolution till ignition, and the ignition must be worked out in the CD scenario.

If the absorbing material in SN 2014J is indeed CSM, it adds to PTF 11kx in supporting the CD scenario. In PTF 11kx the CD scenario is the only one among the scenarios studied here that can account for the mass and properties of the CSM (Soker et al. 2013). Including other observational properties of SN Ia that were listed by Tsebrenko & Soker (2015a) in their table 1, I find the CD scenario to be the favorable one for SN Ia, possibly together with the DD scenario. The automatic attribution of any CSM material around SN Ia to the SD scenario should be abandoned. The CD scenario does much better.

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