[O I] $\lambda\lambda6300, 6364$ IN THE NEBULAR SPECTRUM OF A SUBLUMINOUS TYPE IA SUPERNOVA[*]

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ABSTRACT

In this letter a late-phase spectrum of SN 2010lp, a subluminous Type Ia supernova (SN Ia), is presented and analysed. As in 1991bg-like SNe Ia at comparable epochs, the spectrum is characterised by relatively broad [Fe II] and [Ca II] emission lines. However, instead of narrow [Fe III] and [Co III] lines that dominate the emission from the innermost regions of 1991bg-like SNe, SN 2010lp shows [O I] $\lambda\lambda6300, 6364$ emission, usually associated with core-collapse SNe and never observed in a subluminous thermonuclear explosion before. The [O I] feature has a complex profile with two strong, narrow emission peaks. This suggests oxygen to be distributed in a non-spherical region close to the centre of the ejecta, severely challenging most thermonuclear explosion models discussed in the literature. We conclude that given these constraints violent mergers are presently the most promising scenario to explain SN 2010lp.

Keywords: supernovae: general — supernovae: individual (SN 2010lp, SN 1991bg, SN 1999by)

1. INTRODUCTION

Despite the great success of Type Ia supernovae (SNe Ia) as cosmological distance indicators (Riess et al. 1998; Perlmutter et al. 1999) and the agreement that they represent thermonuclear explosions of CO white dwarfs (WDs) in binary systems (e.g. Bloom et al. 2012; Hillebrandt et al. 2013), the details of their explosion are not yet fully understood. There is e.g. an ongoing debate on the nature of the companion star. Single-degenerate scenarios with slightly evolved main-sequence-star or red-giant companions are supported by the detection of circumstellar material in some SNe Ia (e.g. Patat et al. 2007; Dilday et al. 2012, but see Livio & Riess 2003 and Soker et al. 2013). However, the non-detection of the companion star of the SN 2011fe precursor in multi-wavelength pre-explosion observations (Li et al. 2011; Bloom et al. 2012) and the lack of emission from supersoft X-ray sources in elliptical galaxies (Gilfanov & Bogdán 2010) indicate that at least a fair fraction of all SNe Ia are probably produced by double-degenerate systems where the companion is another WD. Closely related to the question of the progenitor system is that of the explosion mechanism. Once ignited, the thermonuclear flame may propagate subsonically (deflagration), supersonically (detonation), or undergo a deflagration-to-detonation transition (e.g. Hillebrandt et al. 2013).

A powerful way to distinguish between different progenitor scenarios and explosion mechanisms is by identifying their characteristic nucleosynthesis footprints in observed SNe Ia, since the distribution of nucleosynthesis products varies between models. In pure deflagrations, for instance, the ejecta are thoroughly mixed owing to turbulent burning (e.g. Röpke & Niemeyer 2007; Ma et al. 2013). Freshly synthesised iron-group elements (IGEs) are present even in the outermost ejecta, while unburned material is mixed to the core. The influence on the spectral evolution is significant: pure deflagrations may explain the subclass of peculiar 2002cx-like SNe (Jha et al. 2006; Foley et al. 2013; Kromer et al. 2013), but not the bulk of SNe Ia. Pure detonations and delayed detonations produce stratified ejecta, in better agreement with observations of normal SNe Ia (e.g. Höflich & Khokhlov 1996; Kasen et al. 2009; Sim et al. 2010).

Spectra of SNe Ia taken around peak brightness probe the outer layers of the ejecta rich in intermediate-mass elements (IMEs) and unburned material. Only at later phases do the ejecta become sufficiently transparent to directly see emission from the IGE-rich core. Nebular spectra of SNe Ia have therefore been recognised as a highly useful tool to study nucleosynthesis and geometry effects in SNe Ia (e.g. Axelrod 1980; Kozma et al. 2005; Maeda et al. 2010), with important consequences for the preferred explosion scenarios.

All known nebular spectra of SNe Ia are dominated by IGEs, most notably by forbidden emission lines of Fe II and Fe III, consistent with inner ejecta mainly composed of IGEs produced in explosive Si burning. In some SN Ia subclasses (subluminous 1991bg-like objects, 2002cx-like objects and some superluminous SNe Ia, see Mazzali et al. 1997; Jha et al. 2006; Taubenberger et al. 2013) prominent [Ca II] $\lambda\lambda7291, 7323$ has been detected, but this is most likely an ionisation rather than an abundance effect, with Ca being less highly ionised in the overall 'cooler' ejecta of those objects. A feature often searched for in nebular spectra of SNe Ia is the [O I] $\lambda\lambda6300, 6364$ doublet. Its presence would reveal unburned material in the inner parts of the ejecta, ruling out most of the proposed explosion mechanisms. However, so far [O I] emission has never been detected in a subluminous SN Ia, and only in a single normal SN Ia, the ancient SN 1937C (Minkowski 1939).

In this letter we present a late-time spectrum of the subluminous SN Ia 2010lp that shows a prominent emission feature

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at ~ 6300 Å, probably due to [O I] $\lambda\lambda 6300, 6364$. We analyse the line profile to constrain the spatial distribution of the emitting material, and consider what an [O I] emission implies in terms of explosion scenarios. Finally, we discuss under what circumstances unburned material in the centre of SN Ia ejecta may or may not produce an observable signature in form of late-time [O I] $\lambda\lambda 6300, 6364$ emission.
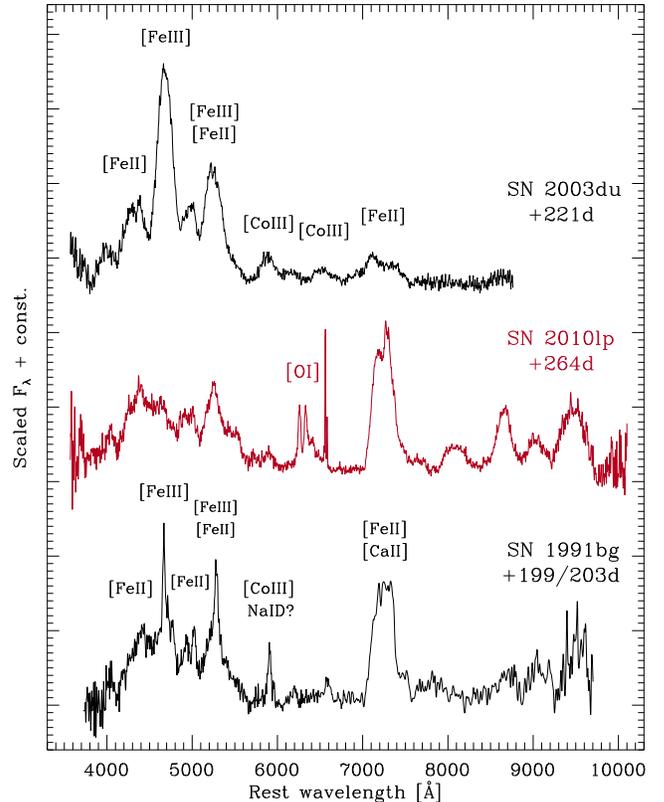
2. SN 2010LP

SN 2010lp was discovered on UT 2010 December 29.16 by Cox et al. (2010) in the course of the Puckett Observatory Supernova Search at an apparent unfiltered magnitude of 16.7. It was located at $\alpha = 02^h 54^m 03{.}^s 50$, $\delta = +02°57'43{.}''4$ (J2000), 13.2 arcsec east of the centre of NGC 1137, at a heliocentric redshift $z = 0.010$ (Huchra et al. 1999). Based on a spectrum taken on UT 2010 December 30–31, Prieto & Morrell (2011) classified SN 2010lp as a subluminous SN Ia resembling SN 2007on (Stritzinger et al. 2011) around maximum light.

Given the peculiar nature of the SN, its relative proximity and the availability of early-time follow-up observations (Pignata et al. in prep.), we selected SN 2010lp as a target for our programme on nebular SN Ia spectroscopy with VLT + FORS2. Spectra were taken on UT 2011 September 27–29 (grism 300V) and UT 2011 September 29–30 (grism 300I) with a 1.0 arcsec slit, an atmospheric-dispersion corrector and exposure times of 3×2700 s for each grism. They were pre-reduced following standard recipes within IRAF, followed by an optimal, variance-weighted extraction (Horne 1986). The dispersion solution was established using arc-lamp exposures and checked against isolated nightsky lines. Observations of spectrophotometric standard stars obtained during the same nights were used to calibrate the spectra in flux and to remove telluric absorptions. Given the late phase of the SN (264 d after maximum light; Pignata priv. comm.) no relevant evolution is expected over the 3 days of our observations. We therefore combined all spectra to increase the signal-to-noise ratio and maximise the wavelength coverage.

As in other SNe Ia at late epochs, the resulting spectrum (Fig. 1) is dominated by forbidden emission lines of Fe, but the ionisation state of the ejecta is low. [Fe III] lines, normally the hallmark features of nebular SN Ia spectra, are weak or absent, similar to what is observed in other subluminous SNe Ia (Mazzali et al. 1997; Mazzali & Hachinger 2012). Instead, the blue part of the spectrum up to ~ 5500 Å is dominated by pseudo-continuous emission from [Fe II] lines. A strong emission feature at 7000–7500 Å can be attributed to a combination of [Fe II] lines (most notably [Fe II] $\lambda 7155$) and [Ca II] $\lambda\lambda 7291, 7323$. The strength of this feature is another indication of a low ejecta ionisation, since in normal SNe Ia calcium is predominantly doubly ionised at those epochs.

Unprecedented in subluminous SNe Ia is the emission feature seen at ~ 6300 Å. In SNe Ib/c, this feature is typically the most prominent emission line at nebular epochs, and regularly attributed to [O I] $\lambda\lambda 6300, 6364$ (e.g. Taubenberger et al. 2009). The presence or absence of this feature has often been considered the sharpest observational discrimination between core-collapse and thermonuclear SNe (e.g. Filippenko 1997). In SN 2010lp, we observe it in a SN that is decidedly a SN Ia as judged from its early-time spectrum (Prieto & Morrell 2011) and the dominance of forbidden Fe lines in the nebular spectrum. We attribute the well-isolated emission (Fig. 1 – compare with SN 1991bg) to [O I] as in core-collapse SNe;


Figure 1. Nebular spectrum of SN 2010lp, compared with spectra of the normal SN Ia 2003du (Stanishev et al. 2007) and the subluminous SN Ia 1991bg (Turatto et al. 1996; R. Lopez priv. comm.) at similar epochs. The most important lines are identified.

IGEs, which are dominant in other parts of the spectrum, are – owing to their complex level structure – unlikely to produce single isolated features.

3. DISCUSSION

3.1. [O I] line profile

Line profiles in nebular spectra are one-dimensional line-of-sight projections of the three-dimensional emissivity distribution in the ejecta. Analysing line profiles thus constrains the geometry of the emission region, i.e. that part of the ejecta where 1) the emitting chemical species is abundant, 2) has the correct ionisation state, and 3) the upper level of the respective transition is sufficiently populated. At the given epoch, the ionisation and excitation state are largely determined by collisions of atoms with fast electrons and positrons originating from the decay of radioactive elements such as ^{56}Co. This means that besides the oxygen distribution the spatial distribution of ^{56}Ni / ^{56}Co is relevant. For [O I] $\lambda\lambda 6300, 6364$ line-profile analyses are complicated by the doublet nature of the line, with an intensity ratio depending on the ambient matter density (e.g. Leibundgut et al. 1991; Spyromilio & Pinto 1991). In the following analysis we assume the ratio of [O I] $\lambda 6300$ to [O I] $\lambda 6364$ to be ~ 3:1, appropriate for the optically thin limit. This is supported by the non-detection of [O I] $\lambda 5577$, which would be prominent if densities were higher. We fit the profile of the [O I] $\lambda\lambda 6300, 6364$ feature with multiple components following Taubenberger et al. (2009), where each component actually consists of two Gaussian profiles with the same full width at half maximum (FWHM), a fixed separation of 63.5 Å and an intensity ratio of 3:1.
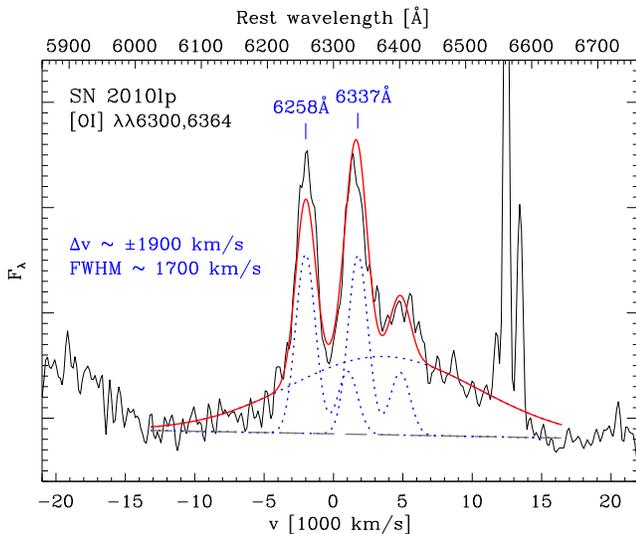
Figure 2. Profile of the [O I] $\lambda\lambda 6300, 6364$ line in SN 2010lp, and its reproduction – within the Gauss-fitting approach of Taubenberger et al. (2009) – as a double-peaked structure atop a broad base. The narrow components have velocity offsets of $\sim \pm 1900$ km s^{-1} from the rest position, and FWHM velocities of ~ 1700 km s^{-1}.
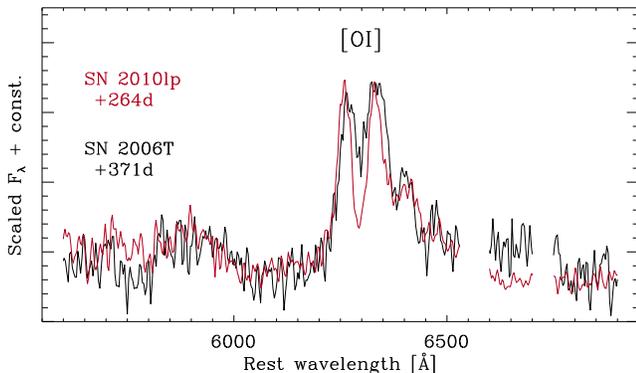
Figure 3. Comparison of the [O I] $\lambda\lambda 6300, 6364$ line profiles in SN 2010lp and the Type IIb SN 2006T (Maeda et al. 2008). A geometric origin has been put forward for the [O I] line profile of SN 2006T (Maeda et al. 2008; Taubenberger et al. 2009).

In SN 2010lp the [O I] $\lambda\lambda 6300, 6364$ feature consists of two similarly strong, fairly narrow emission peaks on top of a broad base (Fig. 2). One of the narrow components is blueshifted with respect to the [O I] $\lambda 6300$ rest wavelength, the other redshifted. Their separation is about 79 Å, too large for them to originate from the two lines of the [O I] doublet (with an intensity ratio of $\sim 1:1$ as expected in the optically thick limit). Instead, the observed line profile likely results from a complex geometry of the emission region, a conclusion also drawn for stripped-envelope core-collapse SNe with similar [O I] profiles (e.g. Maeda et al. 2008; Taubenberger et al. 2009, see Fig. 3).

In our Gauss-fitting approach we reproduce the profile with three components (Fig. 2). The broad base has a FWHM of $\sim 15\,000$ km s^{-1} and is redshifted by ~ 2900 km s^{-1}. It is very likely a blend of [O I] with other lines, possibly [Co III]. This could explain both the unusual width and the apparent redshift. The narrow components have FWHM velocities of ~ 1700 km s^{-1} and blue-/redshifts of 2000 and 1800 km s^{-1}, respectively. Geometrically this could be interpreted as a large volume where some O I is present and emits at low intensity,

complemented by a higher concentration of O I at low velocity responsible for the narrow emission features. To obtain the observed double-peaked profile, the inner O I emission region cannot be spherically symmetric, but could e.g. consist of two compact oxygen-rich blobs with opposite line-of-sight velocity, or a torus-like structure viewed sideways (Mazzali et al. 2005; Taubenberger et al. 2009).

3.2. *Comparison to other subluminous SNe Ia*

A comparison of the nebular spectrum of SN 2010lp and those of the subluminous SNe 1991bg and 1999by (Turatto et al. 1996; Silverman et al. 2012) is particularly insightful, since they share several peculiarities distinguishing them from late-time spectra of normal SNe Ia (Figs. 1 and 4). The strongest and most characteristic features in nebular spectra of normal SNe Ia, i.e. broad (FWHM 7000–10 000 km s^{-1}) [Fe III] emission lines, are absent in all subluminous objects. The pattern of emission features arising from Fe II and Ca II, on the other hand, is remarkably similar in SNe 1991bg, 1999by and 2010lp, suggesting that chemical composition and ionisation state in these three SNe are almost identical throughout most of the ejecta.

However, a significant difference is found in the emission arising from the innermost zones. The spectra of 'classical' subluminous SNe Ia show prominent narrow [Fe III] and [Co III] emission lines (FWHM ~ 2000 and ~ 3600 km s^{-1} in SNe 1991bg and 1999by, respectively) which are entirely absent in SN 2010lp. In the latter, in contrast, narrow [O I] emission is detected with similar FWHM, not present in SNe 1991bg and 1999by. However, what might appear to be a simple 'replacement' of iron by oxygen as the dominant coolant in the innermost regions of SN 2010lp is actually more complicated. First of all, the [O I] emission in SN 2010lp is double-peaked, whereas the [Fe III] emission lines in SNe 1991bg and 1999by are single-peaked, suggesting a different geometrical configuration of the emitting material. Moreover, while the innermost ejecta in SNe 1991bg and 1999by must be more highly ionised than the surrounding material to give rise to strong [Fe III] lines [Mazzali & Hachinger (2012) consider this an indication for a low-density core], the ionisation in the [O I]-emitting region in SN 2010lp has to be rather low in order to retain enough neutral oxygen.

3.3. *Confronting explosion models with SN 2010lp observations*

To explain the narrow [O I] emission detected in the nebular spectrum of SN 2010lp is a severe challenge for SN Ia explosion models. In fact, the constraints on possible models are so stringent that most scenarios discussed today can be rejected for SN 2010lp.

In pure deflagrations turbulent burning leads to thoroughly mixed ejecta, with both IGEs and carbon/oxygen abundant at all velocities (e.g. Röpke & Niemeyer 2007; Ma et al. 2013). [O I] emission in nebular spectra might be expected in this scenario. However, given the rather uniform distribution of unburned material, there is no reason for the [O I] emission to be mostly confined to a small region close to the centre of the ejecta, as observed in SN 2010lp. Indeed Kozma et al. (2005) found prominent *broad* [O I] emission in a synthetic nebular spectrum for a pure-deflagration model. The thorough mixing in deflagrations also enriches the outer ejecta layers with IGEs compared to other scenarios. This results in peculiar early-time spectra, long speculated (Jha et al. 2006;
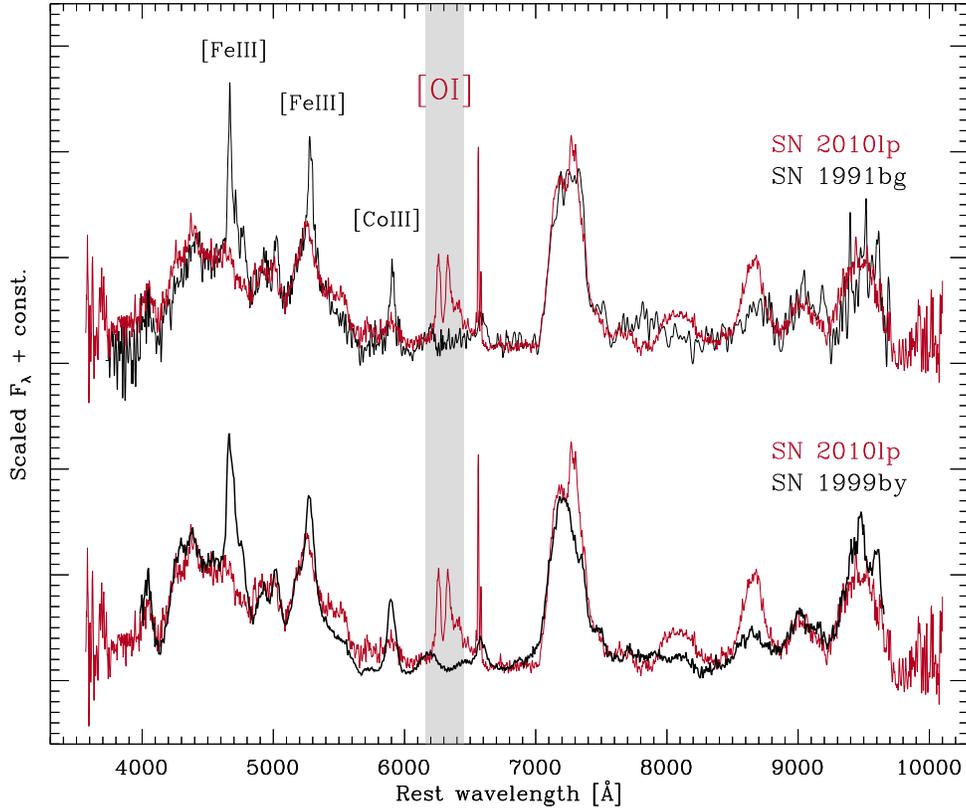
Figure 4. Spectrum of SN 2010lp (+264 d) overplotted on spectra of the subluminous SNe 1991bg (+199 / 203 d) and 1999by (+183 d; Silverman et al. 2012). [O I] $\lambda\lambda 6300, 6364$, which is clearly detected in SN 2010lp but absent in SNe 1991bg and 1999by, is highlighted.

Phillips et al. 2007) and recently shown (Kromer et al. 2013) to be similar to 2002cx-like SNe. Clearly, this disagrees with the description of the early-phase spectrum of SN 2010lp (Prieto & Morrell 2011). Taken together, pure deflagrations are very unlikely to explain SN 2010lp.

In Chandrasekhar-mass (M_{Ch}) delayed-detonation scenarios (e.g. Höflich & Khokhlov 1996; Kasen et al. 2009; Jordan et al. 2012; Seitenzahl et al. 2013), still considered to be favourable models for SNe Ia, the centre is entirely dominated by IGEs. [O I] emission from the core is very unlikely for these models. Similarly, no oxygen is expected to remain in the central ejecta of most pure-detonation scenarios, including sub-M_{Ch} double detonations and edge-lit detonations (e.g. Nomoto 1982; Livne 1990; Fink et al. 2010) as well as spontaneous detonations in sub-M_{Ch} WD-merger remnants (van Kerkwijk et al. 2010). In all these scenarios the central density is high enough for the detonation to convert the fuel almost completely into IGEs.

There is probably only a single SN Ia explosion channel discussed in the literature that may yield oxygen in a narrow region close to the centre of the ejecta: violent mergers (Pakmor et al. 2010, 2012). In these models the primary WD ignites dynamically on the surface. Depending on its mass, the emerging detonation burns most of the primary to IGEs and IMEs. Once the secondary is hit by the ejecta, it also ignites. However, since the density in the less massive and tidally deformed secondary is lower, nuclear burning predominantly proceeds to oxygen, which is ejected at relatively low velocity. If the mass combination of the two WDs is sufficiently asymmetric as in the $1.1 + 0.9\,M_\odot$ merger of Pakmor et al. (2012), oxygen even fills the innermost regions of the combined ejecta of the primary and secondary,

distributed aspherically (see Fig. 2 of Pakmor et al. 2012).

Of course, the $1.1 + 0.9\,M_\odot$ WD merger of Pakmor et al. (2012) produces $0.61\,M_\odot$ of ^{56}Ni, and the early-time spectra do not resemble subluminous SNe Ia as reported for SN 2010lp. However, a setup with a similar ratio of secondary to primary mass (~ 0.8), but a less massive primary, might produce sufficiently little ^{56}Ni yet still leave oxygen close to the centre of the ejecta.

3.4. *Conditions for [O I] formation*

In the qualitative analysis performed here we can only determine a necessary condition for low-velocity [O I] to be observed in nebular spectra: the presence of neutral oxygen close to the core of the ejecta. Whether this is sufficient cannot be assessed without full NLTE modelling of the plasma state, since the formation of the line may depend on details of the ejecta structure.

First of all, the relative location of oxygen and ^{56}Ni / ^{56}Co is crucial. A location sufficiently close to radioactive material helps to populate the upper level of the [O I] $\lambda\lambda 6300, 6364$ lines. However, too much heating by radioactive decay will ionise oxygen too strongly. Moreover, if oxygen is mixed with IGEs on microscopic scales, the ejecta might mostly cool in the numerous forbidden lines of Fe rather than [O I] $\lambda\lambda 6300, 6364$.

From these considerations it is clear that the sheer presence of oxygen in the central part of the ejecta in violent-merger models may not necessarily give rise to [O I] $\lambda\lambda 6300, 6364$ emission at late epochs. Therefore, SN 2010lp may not be unique in having a core formed at least partially by oxygen. In more luminous SNe Ia this may also be present, but ionised owing to the more intense radiation field. Hence, in

spite of its oxygen core the 1.1 + 0.9 M$_\odot$ WD merger of Pakmor et al. (2012) could still be a viable model for normally bright SNe Ia, where nebular [O I] emission has never been observed. 1991bg-like SNe, however, have low ^{56}Ni masses, and share many similarities with SN 2010lp. To avoid [O I] emission in those objects, one cannot allow for much oxygen to be present near the centre of the ejecta. This could be achieved if they were the outcome of violent mergers of CO with He WDs, as proposed by Pakmor et al. (2013).

4. CONCLUSIONS

A late-phase spectrum of the subluminous Type Ia SN 2010lp, taken ~ 264 d after maximum light, shares strong similarities with spectra of 1991bg-like SNe Ia at comparable epochs, being dominated by emission of [Fe II] and [Ca II] lines. However, 1991bg-like SNe additionally show narrow [Fe III] and [Co III] lines, which are absent in SN 2010lp. The latter instead shows a prominent feature near 6300 Å, which constitutes the first clear detection of [O I] $\lambda\lambda6300, 6364$ in a nebular spectrum of a subluminous thermonuclear SN. Previously, [O I] $\lambda\lambda6300, 6364$ has been considered as the most direct observational evidence for a core-collapse origin of an explosion.

The profile of the [O I] line is complex, formed by two narrow emission peaks, one blue- and the other redshifted with respect to the rest wavelength. The separation of these two features is too large to be explained by the doublet nature of [O I] $\lambda\lambda6300, 6364$. Therefore, we favour a geometric origin of the observed profile, with a concentration of oxygen in a non-spherical region close to the centre of the ejecta.

Most thermonuclear explosion models discussed in the literature do not predict the presence of oxygen at low velocity and can therefore be excluded for SN 2010lp. Pure-deflagration models do predict oxygen throughout their strongly mixed ejecta, but no concentration in the inner regions, so that the narrow emission peaks observed in SN 2010lp cannot be explained. Moreover, pure deflagrations are ruled out from the early spectra of SN 2010lp being similar to 1991bg-like SNe. In some violent-merger models, however, oxygen is left near the centre of the ejecta (Pakmor et al. 2011, 2012), making this the most promising scenario for SN 2010lp currently available.

In the end, detailed 3D nebular spectrum synthesis calculations are needed to better constrain the amount of oxygen, its spatial distribution and the degree of mixing with ^{56}Ni and its decay products necessary to reproduce the complex [O I] $\lambda\lambda6300, 6364$ profile observed in SN 2010lp. The ejecta structure obtained from hydrodynamic simulations of violent mergers may serve as a starting point in such a modelling approach.

REFERENCES

Axelrod, T. S. 1980, PhD thesis, University of California, Santa Cruz
Bloom, J. S., Kasen, D., Shen, K. J., et al. 2012, ApJ, 744, L17
Cox, L., Newton, J., Puckett, T., & Walters, S. 2010, Central Bureau Electronic Telegrams, 2612, 1
Dilday, B., Howell, D. A., Cenko, S. B., et al. 2012, Science, 337, 942
Filippenko, A. V. 1997, ARA&A, 35, 309
Fink, M., Röpke, F. K., Hillebrandt, W., et al. 2010, A&A, 514, A53
Foley, R. J., Challis, P. J., Chornock, R., et al. 2013, ApJ, 767, 57
Gilfanov, M., & Bogdán, Á. 2010, Nature, 463, 924
Hillebrandt, W., Kromer, M., Röpke, F. K., & Ruiter, A. J. 2013, Frontiers of Physics, 8, 116
Höflich, P., & Khokhlov, A. 1996, ApJ, 457, 500
Horne, K. 1986, PASP, 98, 609
Huchra, J. P., Vogeley, M. S., & Geller, M. J. 1999, ApJS, 121, 287
Jha, S., Kirshner, R. P., Challis, P., et al. 2006, AJ, 131, 527
Jordan, IV, G. C., Graziani, C., Fisher, R. T., et al. 2012, ApJ, 759, 53
Kasen, D., Röpke, F. K., & Woosley, S. E. 2009, Nature, 460, 869
Kozma, C., Fransson, C., Hillebrandt, W., et al. 2005, A&A, 437, 983
Kromer, M., Fink, M., Stanishev, V., et al. 2013, MNRAS, 429, 2287
Leibundgut, B., Kirshner, R. P., Pinto, P. A., et al. 1991, ApJ, 372, 531
Li, W., Leaman, J., Chornock, R., et al. 2011, MNRAS, 412, 1441
Livio, M., & Riess, A. G. 2003, ApJ, 594, L93
Livne, E. 1990, ApJ, 354, L53
Ma, H., Woosley, S. E., Malone, C. M., Almgren, A., & Bell, J. 2013, ApJ, 771, 58
Maeda, K., Kawabata, K., Mazzali, P. A., et al. 2008, Science, 319, 1220
Maeda, K., Taubenberger, S., Sollerman, J., et al. 2010, ApJ, 708, 1703
Mazzali, P. A., Chugai, N., Turatto, M., et al. 1997, MNRAS, 284, 151
Mazzali, P. A., Kawabata, K. S., Maeda, K., et al. 2005, Science, 308, 1284
Mazzali, P. A., & Hachinger, S. 2012, MNRAS, 424, 2926
Minkowski, R. 1939, ApJ, 89, 156
Nomoto, K. 1982, ApJ, 257, 780
Pakmor, R., Kromer, M., Röpke, F. K., et al. 2010, Nature, 463, 61
Pakmor, R., Hachinger, S., Röpke, F. K., & Hillebrandt, W. 2011, A&A, 528, A117+
Pakmor, R., Kromer, M., Taubenberger, S., et al. 2012, ApJ, 747, L10
Pakmor, R., Kromer, M., Taubenberger, S., & Springel, V. 2013, ApJ, 770, L8
Patat, F., Chandra, P., Chevalier, R., et al. 2007, Science, 317, 924
Perlmutter, S., Aldering, G., Goldhaber, G., et al. 1999, ApJ, 517, 565
Phillips, M. M., Li, W., Frieman, J. A., et al. 2007, PASP, 119, 360
Prieto, J. L., & Morrell, N. 2011, Central Bureau Electronic Telegrams, 2613, 1
Riess, A. G., Filippenko, A. V., Challis, P., et al. 1998, AJ, 116, 1009
Röpke, F. K., & Niemeyer, J. C. 2007, A&A, 464, 683
Seitenzahl, I. R., Ciaraldi-Schoolmann, F., Röpke, F. K., et al. 2013, MNRAS, 429, 1156
Silverman, J. M., Foley, R. J., Filippenko, A. V., et al. 2012, MNRAS, 425, 1789
Sim, S. A., Röpke, F. K., Hillebrandt, W., et al. 2010, ApJ, 714, L52
Soker, N., Kashi, A., García-Berro, E., Torres, S., & Camacho, J. 2013, MNRAS, 431, 1541
Spyromilio, J., & Pinto, P. A. 1991, in European Southern Observatory Conference and Workshop Proceedings, Vol. 37, European Southern Observatory Conference and Workshop Proceedings, ed. I. J. Danziger & K. Kjaer, 423
Stanishev, V., Goobar, A., Benetti, S., et al. 2007, A&A, 469, 645
Stritzinger, M. D., Phillips, M. M., Boldt, L. N., et al. 2011, AJ, 142, 156
Taubenberger, S., Valenti, S., Benetti, S., et al. 2009, MNRAS, 397, 677
Taubenberger, S., Kromer, M., Hachinger, S., et al. 2013, MNRAS, 432, 3117
Turatto, M., Benetti, S., Cappellaro, E., et al. 1996, MNRAS, 283, 1
van Kerkwijk, M. H., Chang, P., & Justham, S. 2010, ApJ, 722, L157