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Spectroscopy of the Type Ia supernova 2011fe past 1000 d

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ABSTRACT

In this Letter we present an optical spectrum of SN 2011fe taken 1034 d after the explosion, several hundred days later than any other spectrum of a Type Ia supernova (disregarding light-echo spectra and Local Group remnants). The spectrum is still dominated by broad emission features, with no trace of a light echo or interaction of the supernova ejecta with surrounding interstellar material. Comparing this extremely late spectrum to an earlier one taken 331 d after the explosion, we find that the most prominent feature at 331 d – [Fe III] emission around 4700 Å – has entirely faded away, suggesting a significant change in the ionization state. Instead, [Fe II] lines are probably responsible for most of the emission at 1034 d. An emission feature at 6300–6400 Å has newly developed at 1034 d, which we tentatively identify with Fe I λ6359, [Fe I] λλ6231, 6394 or [O I] λλ6300, 6364. Interestingly, the features in the 1034 d spectrum seem to be collectively redshifted, a phenomenon that we currently have no convincing explanation for. We discuss the implications of our findings for explosion models, but conclude that sophisticated spectral modelling is required for any firm statement.

Key words: line: identification – supernovae: general – supernovae: individual: SN 2011fe.

1 INTRODUCTION

For several years after the explosion, the luminosity of Type Ia supernovae (SNe Ia) is powered by the decay of radioactive nuclei synthesized in the explosion. At the beginning, the ejecta are still optically thick, and the radiation is released on photon-diffusion time-scales. About 100–200 d later, the ejecta have expanded enough to become transparent for optical photons. During the now-commencing nebular phase, the radioactive-heating and radiative-cooling rates are similar, making the bolometric luminosity evolution a good tracer of the radioactive energy deposition.

Cooling during the nebular phase is mostly accomplished by forbidden-line emission: low-lying levels that are still populated at such late epochs often have no permitted transition to the ground state, and collisional de-excitation is strongly suppressed owing to the low density. The dominant coolants in nebular SNe Ia are iron-group elements, reflecting the composition of the inner ejecta. In particular, optical spectra of SNe Ia around one year after the explosion show a characteristic pattern of [Fe II] and [Fe III] lines.

The past decade has led to a wealth of high-quality late-time spectra of SNe Ia. This made it possible to study nucleosynthesis and geometry effects in SNe Ia in unprecedented detail (e.g. Kozma et al. 2005; Maeda et al. 2010a,b; Mazzali et al. 2011; Blondin et al. 2012; Silverman, Ganeshalingam & Filippenko 2013; Taubenberger et al. 2013a). However, all these studies concentrated on epochs between 200 and 400 d after the explosion. Beyond 400–500 d, our knowledge on the spectroscopic evolution of SNe Ia is limited. Whenever an SN Ia was bright enough to perform spectroscopy at such late phases, as e.g. in the cases of SNe 1991T or 1998bu, it was dominated by a light echo (Schmidt et al. 1994; Cappellaro et al. 2001, respectively), prohibiting the study of actual late-time emission from the SN ejecta.[1]

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[1] A spectrum of SN 1972E obtained ∼700 d after maximum light (Kirshner & Oke 1975) suffers from low resolution, poor signal-to-noise ratio (S/N) and limited wavelength coverage. A spectrum of SN 2005cf taken 614 d

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The few model calculations that exist for those phases also suffer from numerous uncertainties. To capture the relevant nebular physics (e.g. McCray 1993; Fransson 1994), non-thermal processes have to be accurately modelled, which is sometimes impossible due to missing or inaccurate atomic data. Moreover, owing to the low ejecta densities, which lead to increased recombination time-scales, departures from steady state arise. As a consequence, ionization freeze-out may occur (Fransson & Kozma 1993; Fransson, Houck & Kozma 1996). For this reason, a fully time-dependent treatment becomes essential after ∼500 d (Sollerman et al. 2004) to predict the correct ionization state of the ejecta. Spectra observed at epochs >500 d could greatly help to assess the correctness of model calculations, and hence provide a big step forward in our understanding of both nebular physics and SN Ia explosions.

With SN 2011fe (Nugent et al. 2011), this goal is now for the first time in reach. Its proximity (d = 6.4 Mpc; Shappee & Stanek 2011), low dust extinction and relatively uncrowded environment make SN 2011fe the ideal object to push observations to new limits. Kerzendorf et al. (2014) recently reported multiband optical photometry of SN 2011fe between 900 and 950 d after the explosion, concluding that the light-curve decline is consistent with radioactive decay, and that there is no evidence for positron escape, an infrared catastrophe (IRC; Axelrod 1980), dust formation, or a light echo. The derived colours were still remarkably blue. Here, we present a spectrum of SN 2011fe taken ∼100 d later – the first nebular spectrum of an SN Ia ever obtained at more than 1000 d after its explosion – and compare it with a spectrum taken after ∼1 yr.

2 DATA ACQUISITION AND REDUCTION

A spectrogram of SN 2011fe was obtained on 2012 July 20.02 (UT dates are used throughout this Letter), 331 rest-frame days after its inferred explosion on 2011 August 23.687 (Nugent et al. 2011), with the OSIRIS spectrograph at the Gran Telescopio Canarias (GTC). Two grisms (R1000B and R1000R) were used, with an exposure time of 300 s for each grism, and a 1.0 arcsec slit aligned along the parallactic angle. Basic CCD reductions and a variance-weighted extraction of the spectra were carried out within IRAF.[2] The wavelength calibration was accomplished using arc-lamp exposures and checked against night-sky lines. A spectrophotometric standard star observed during the same night as the SN was used for flux calibration and telluric-feature removal.

SN 2011fe was again targeted on 2014 June 23.22, 1034 rest-frame days after the explosion, when the SN had faded to $i' \sim 24$. The observations were carried out at the Large Binocular Telescope (LBT), equipped with the MODS1 dual-beam spectrograph, during Italian/INAF time. Three exposures of 3600 s each were taken in good seeing conditions (0.6–1.0 arcsec FWHM) through a 1.0 arcsec slit, aligned along the mean parallactic angle over the time of the observations (see Fig. 1). A dichroic split the light beam at 575 nm, and the G400L and G670L gratings were used as dispersers for the blue and red channel, respectively. The data were pre-reduced using the MODSCCDRED package,[3] and the extraction and calibration of the spectra followed the same scheme as described for the GTC data. Eventually, the individual medium-resolution spectra were combined and rebinned to 5 Å bins.

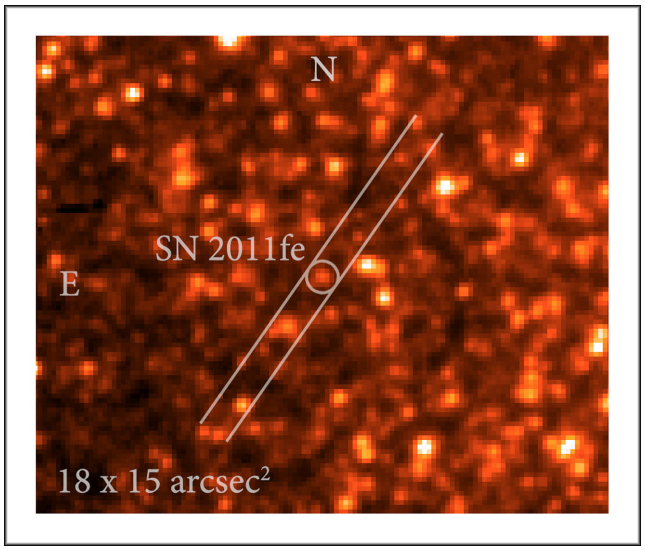


Figure 1. 18 × 15 arcsec^2 section of an i'-band image, taken with the Gemini-N Telescope + GMOS-N four days after our LBT spectrum. North is up, east to the left. The width and orientation of the 1 arcsec slit used for the LBT observations are indicated.

3 DISCUSSION

3.1 Line identification

In Fig. 2, our nebular spectra of SN 2011fe are presented. At +331d the line identification is relatively straightforward and follows earlier work in this area (for example, see Maeda et al. 2010b). The strong emissions between 4000 and 5500 Å are well fitted by non-LTE excitation of iron by an ∼4000 K thermal electron gas (e.g. Axelrod 1980). The feature around 4700 Å is dominated by [Fe III], with only a small contribution from [Fe II]. The 5250 Å feature is a blend of [Fe III] and [Fe II]. Other features, notably the [Fe II] λ7155 / [Ni II] λ7378 blend around 7200 Å, are marked in Fig. 2.

By day 1034 dramatic changes have occurred. The formerly very prominent [Fe III] line at 4700 Å has disappeared, while the 4400 and 5300 Å features have preserved their line ratios and now dominate the flux in the optical regime. The 7200 Å feature has weakened relative to the strong emission in the 5000 Å region. The comparison of the 1034 and 331 d spectra naturally leads to the conclusion that the ionization structure of the ejecta has changed and only little Fe III is present.

However, the spectrum is difficult to reconcile with thermal excitation. The 7200 Å feature has a contribution from Fe II multiplet 14F (a ^{4}F – a ^{2}G) with an upper level at ∼2 eV, whereas the bulk of the 4000–5500 Å lines arise from Fe II multiplets [e.g. 6F (a ^{6}D – b ^{4}F), 18F (a ^{4}F – b ^{4}P), 19F (a ^{4}F – a ^{4}H)] with upper levels near 2.5 eV. Only a hot (∼8000 K) electron gas could reproduce this spectrum. This is an unrealistically high temperature for an SN 1000 d after explosion, and in conflict with the observed low ionization. There are likely contributions by Fe I multiplets 2F (a ^{5}D – a ^{5}P) and 3F (a ^{5}D – a ^{3}P2) to the 5300 Å feature, and by multiplets 4F (a ^{5}D – b ^{3}F2) and 6F (a ^{5}D – b ^{3}P) to the 4400 Å feature. Again, the observed ratio of the 4400 to the 5300 Å feature is not in agreement with thermal excitation at any realistic temperature. Recombination or non-thermal excitation processes must therefore prevail.

after maximum light (Wang et al. 2009) turns out to be that of an M-type star upon closer inspection.

[2] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy under cooperative agreement with the National Science Foundation.

[3] http://www.astronomy.ohio-state.edu/MODS/Software/modsCCDRed/

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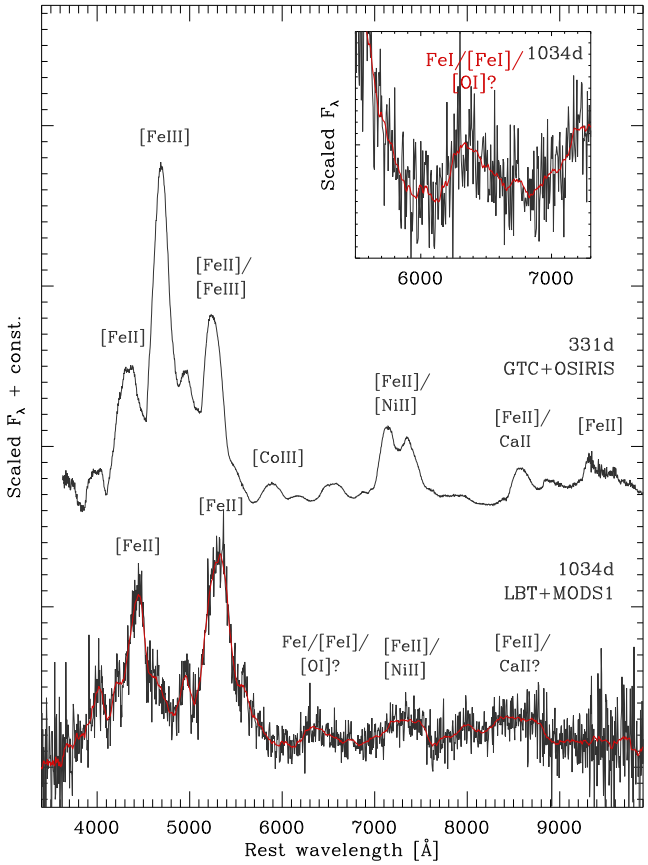


Figure 2. Nebular spectra of SN 2011fe, along with an attempted line identification. A smoothed version (with a boxcar of ∼5000 km s^{-1}; solid red line) is overlaid on the 1034 d spectrum to facilitate the assessment of line profiles. The inset enlarges the region of the possible Fe I or [O I] feature.

The series of cobalt lines between 5800 and 6700 Å, still fairly prominent in the 331 d spectrum, is no longer detected at 1034 d. Given that most of the cobalt in SNe Ia is ^{56}Co, which decays with a half-life of 77 d, the observed fading of the cobalt lines is expected. However, in the same region a new, broad emission feature has emerged (see inset of Fig. 2). It is centred around 6360 Å, and might be identified with some combination of Fe I λ6359, [Fe I] λλ6231, 6394 and [O I] λλ6300, 6364. Given the dominance of [Fe II] lines in the spectrum and our proposal that [Fe I] contributes in the 4000–5500 Å range, the identification with Fe I lines may appear more natural. On the other hand, if [O I] can be confirmed through spectral modelling, this would be the third detection of [O I] λλ6300, 6364 in the nebular spectrum of a thermonuclear SN, after SN 1937C (Minkowski 1939) and SN 2010lp (Taubenberger et al. 2013b), though this time only at a much later epoch.

There is no sign of narrow or intermediate-width emission lines that might hint at interaction with interstellar material (ISM). The transition of SN 2011fe into the remnant phase, when the emission becomes dominated by the shock originating from ejecta–ISM collisions, has not yet started. In particular, no narrow Hα line is detected. Such a line might be expected in nebular spectra of single-degenerate explosions, where H-rich material is stripped from a non-degenerate companion star upon the impact of the SN ejecta (Marietta, Burrows & Fryxell 2000; Pakmor et al. 2008; Liu et al. 2012). Thus far, Hα arising from stripped material has never been detected in nebular SN Ia spectra (Mattila et al. 2005; Leonard 2007). With our 1034 d spectrum, we now extend the series of non-detections to much later epochs. Though the presence of a very weak Hα line cannot be excluded because of S/N limitations, our non-detection is in line with the absence of narrow Hα in our 331 d spectrum and in an even higher-S/N spectrum of SN 2011fe taken 275 d after the *B*-band maximum (Shappee et al. 2013).

Kerzendorf et al. (2014) discussed the possibility of a light echo, as in their photometry taken about 950 d after the explosion SN 2011fe appeared bright and blue. They argued, however, that a strong light echo – as e.g. observed in SNe 1991T and 1998bu (Schmidt et al. 1994; Cappellaro et al. 2001, respectively) – was unlikely, since the observed colours did not agree with those of SNe Ia around maximum light, as one would expect for a light echo. With our 1034 d spectrum we can now finally rule out the possibility of a light echo, since no (pseudo-)continuum or P-Cygni features are detected.

3.2 Line shifts

Once an SN has turned transparent to optical photons, emission-line profiles probe the underlying emissivity distribution in the ejecta. The latter depends on the relative location of coolants and radioactive material, and on the mean free paths of γ-rays and positrons. During the epochs under consideration in this Letter (>300 d after the explosion), the ejecta are largely transparent to γ-rays, and the energy deposition is dominated by positrons and electrons (Milne, The & Leising 2001; Seitenzahl, Taubenberger & Sim 2009). Studies of the late-time bolometric luminosity of SNe Ia (Cappellaro et al. 1997; Leloudas et al. 2009; Kerzendorf et al. 2014) have argued for almost complete positron trapping even as late as 900 d, suggesting a rather short mean free path of positrons, and a nearly *in situ* deposition of the radioactive-decay energy during the positron-dominated phase.

Detailed studies of nebular optical and infrared emission-line profiles in SNe Ia have been carried out in the past (Mazzali et al. 1998; Motohara et al. 2006; Gerardy et al. 2007; Maeda et al. 2010a,b). An interesting result of such studies was that certain emission lines (e.g. [Fe II] λ7155 and [Ni II] λ7378; Maeda et al. 2010b) showed significant blue- or redshifts in different SNe, which was interpreted as a viewing-angle effect. Maeda et al. (2010a), finally, found a correlation between the post-maximum velocity gradient in Si II λ6355 (Benetti et al. 2005) and the shift of nebular [Fe II] λ7155 and [Ni II] λ7378 lines. In our 331 d spectrum of SN 2011fe we find both lines to be blueshifted, the [Fe II] λ7155 line by almost 1000 km s^{-1}, the [Ni II] λ7378 line by 1100 km s^{-1}. This meets the expectations, given that SN 2011fe is a low-velocity-gradient SN in the Benetti et al. (2005) classification scheme (e.g. Pereira et al. 2013).

In the 1034 d spectrum the S/N is insufficient to directly measure accurate positions for all except the two strongest emission lines. However, as noted in the previous section, the 331 d and 1034 d spectra appear to have several [Fe II] features in common, and so a superposition of the two spectra (Fig. 3, top panels) can be instructive to determine changes in the line profiles or positions. From Fig. 3, it is immediately evident that there seems to be a global offset in several (if not all) common features, in the sense that the 1034 d spectrum appears globally redshifted with respect to the 331 d spectrum. The shift amounts to 4200 km s^{-1}, as inferred from a cross-correlation of the peaks in the 4000–5500 Å region, with an estimated uncertainty of ±200 km s^{-1}. That this shift is real is demonstrated in the bottom panel of Fig. 3, where no offset is seen in the night-sky spectra of the two observations.

Following the paradigm that nebular spectra probe the ejecta geometry, the observed shift might be understood if the emitting regions of the ejecta were different at 331 and 1034 d. At 331 d

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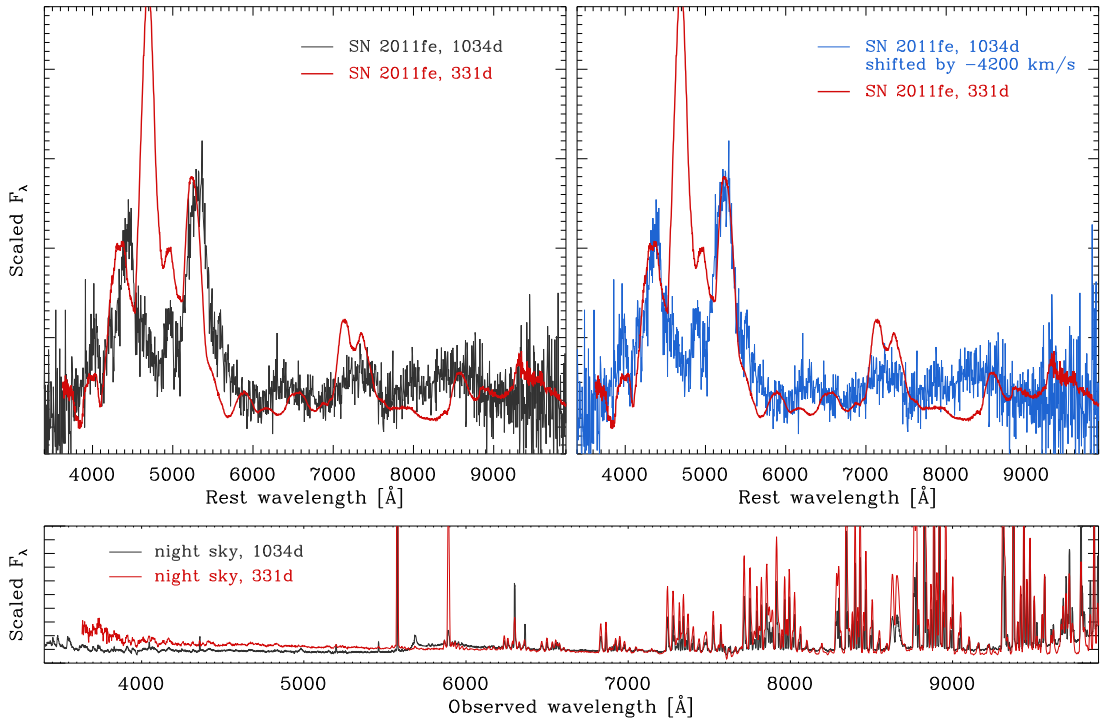


Figure 3. Top-left panel: superposition of the 1034 d and 331 d spectra of SN 2011fe, scaled arbitrarily in flux. A wavelength offset seems to be present in all features that can be identified in both spectra. Top-right panel: the match of features is substantially improved if a wavelength shift corresponding to -4200 km s^{-1} is applied. Bottom panel: no offset is present in the night-sky spectra.

the energy deposition is dominated by positrons from ^{56}Co decay, at 1034 d by electrons and X-rays from ^{57}Co decay (Seitenzahl et al. 2009; Röpke et al. 2012). A spatial separation of ^{56}Co and ^{57}Co could thus lead to the observed effect. However, explosion models (e.g. Seitenzahl et al. 2013) suggest that ^{56}Co and ^{57}Co are synthesized cospatially, making this explanation unlikely. The same is true for the attempt to explain the observed time evolution by residual opacity in the core of the ejecta at 331 d. First, a sufficiently large optical depth to produce line shifts of 4000 km s^{-1} almost one year after the explosion is unreasonable. Secondly, the lines in the 331 d spectrum are close to their rest-frame position, so that we do not have to explain a blueshift at 331 d, but a redshift at 1034 d.

Since the affected features are blends (actually often multiplets), changes in the ionization and excitation conditions might lead to a strengthening or weakening of individual constituents, resulting in an effective shift of the entire blend. Also, if there is indeed a significant contribution by lines from Fe I at 1034 d, wavelength shifts compared to the 331 d spectrum are to be expected. However, it appears rather unlikely that any of these effects leads to the same offset in *all* features throughout the spectrum, though ultimately this has to be verified by accurate spectral modelling.

3.3 Implications for models

Comparing the 1034 d spectrum of SN 2011fe to synthetic nebular spectra would be extremely worthwhile to infer details about the composition, ionization and excitation state of the ejecta. Unfortunately, not many model calculations with at least broad-band spectral information have ever been performed for SNe Ia at such a late phase. One of the most extended non-grey time-dependent model calculations for SNe Ia to date is that by Leloudas et al. (2009). Their synthetic *UBVRIJHK*-band light curves of the W7 model (Nomoto, Thielemann & Yokoi 1984) show a rapid decline starting at ∼500 d, which can be attributed to the onset of an IRC (Axelrod 1980). Such an IRC occurs when the temperature drops below ∼1500 K, too low to populate the upper levels of typical nebular emission lines in the optical and near-IR regime. As a consequence, most of the cooling henceforth happens via fine-structure lines in the mid- and far-IR, leading to a dramatic change of the spectral energy distribution.

Kerzendorf et al. (2014) argued that their 930 d photometry of SN 2011fe showed no evidence of the enhanced fading predicted by an IRC. This conclusion seems to be supported by our 1034 d spectrum, where we still observe prominent emission lines in the optical regime. However, there may be ways to reconcile our observations with an IRC, if the latter is restricted to certain regions of the ejecta while others remain hot,[4] or if the observed lines are actually recombination lines and hence not excited thermally.

As already mentioned in Section 3.1, the 1034 d spectrum of SN 2011fe shows a broad (FWHM ∼12 000 km s^{-1}) emission feature centred at ∼6360 Å, for which Fe I λ6359, [Fe I] λλ6231, 6394 and [O I] λλ6300, 6364 are possible identifications. Interpreted as [O I], the feature would be redshifted by ∼2000 km s^{-1}. If this identification is correct, it has important consequences for the preferred explosion scenario for SN 2011fe in particular and – given the conception of SN 2011fe as a perfectly 'normal' SN Ia – for the entire SN Ia class. To produce late-time [O I] emission with the given line profile, oxygen has to be present in the inner part of the ejecta (the line profile is not flat-topped, which disfavours emission from a shell), which is fulfilled only for a small subset of SN Ia explosion models (Taubenberger et al. 2013b), notably violent mergers (Pakmor et al. 2012; Kromer et al. 2013). However, Jerkstrand,

[4] The critical temperature for an IRC is density-dependent; local density enhancements in form of clumping may significantly postpone the IRC.

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Fransson & Kozma (2011) found that at very late phases, when thermal collisional excitation of [O I] λλ6300, 6364 was no longer possible, even in the arguably much more oxygen-rich SN 1987A the emission feature near 6300 Å was dominated by Fe I recombination lines rather than [O I]. Whether these conditions are met in SN 2011fe at 1034 d, where we still observe relatively high-excitation [Fe II] lines, has to be verified by detailed simulations of the plasma state.

4 CONCLUSIONS

We have presented two optical spectra of SN 2011fe taken 331 and 1034 d after explosion. At 1034 d the emission still comes from the nebular SN ejecta, with no signs of a light echo or interaction with ISM. None the less, strong changes have occurred compared to the early nebular phase. The most striking of these is the complete fading of the 4700-Å [Fe III] emission – the by far most prominent feature at 331 d – which we attribute to a decrease of the ionization state. [Fe II] features, on the contrary, can still be identified. A weak, broad emission feature is now present at ∼6360 Å, which might either be attributed to lines from Fe I, or to [O I] λλ6300, 6364, which would have important consequences for explosion scenarios.

From the features that the 331 d and 1034 d spectra seem to have in common (mostly [Fe II] blends) a relative wavelength shift can be derived, in the sense that at 1034 d all features appear to be redshifted by ∼4000 km s^{-1} compared to the earlier epoch. We currently have no convincing explanation for this unexpected behaviour, and it remains unclear whether the origin of this shift is geometric, optical-depth-related, or a conspiracy of atomic physics.

The detection of prominent emission lines in the 4000–5000 Å range, combined with the late-time luminosity of SN 2011fe reported by Kerzendorf et al. (2014), seems to disfavour the idea that an IRC has taken place in the bulk of the ejecta. In contrast, model calculations predict the onset of an IRC with strong observable consequences already at 500 d (Leloudas et al. 2009). Whether this discrepancy hints at an inadequacy of the W7 explosion model used for those calculations or at shortcomings in the atomic data and nebular-physics treatment has to be tested in future modelling efforts. The 1034 d spectrum of SN 2011fe presented here provides the perfect benchmark for such modelling.

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