The Oxygen 1.13 μm Fluorescence Line of SN1987A: a Diagnostic for the Ejecta of Hydrogen-Rich Supernovae

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The bright O I λ11287 line observed in SN1987A is produced by the Bowen fluorescence with Lyβ and comes from regions that lie within a Sobolev length ($\delta R \sim 10^{-3}\, R_{SN}$, the maximum distance over which fluorescence can work) from hydrogen rich gas ionized by the ^{56}Co decay. Its strength relative to hydrogen lines (e.g. Brγ) depends on the O/H relative abundance in the 'fluorescent region' and on the density (i.e. the filling factor) of the gas. The observed evolution of λ11287 can be successfully understood using a relatively simple theory which takes into account the effects of transfer in the O I lines and is the generalization of the classical theory of Bowen fluorescence.

The most important result is that the time evolution of the relative intensities and profiles of O Iλ11287 and Brγ is a powerful diagnostic to determine:

— The filling factor of the hydrogen rich gas;

— The pre-SN O/H relative abundance;

— The amount of small scale mixing between hydrogen and oxygen rich regions and its radial stratification.

In SN1987A the results are the following:

— Inside 2000 km/s the hydrogen rich material is clumped with $f \simeq 0.1$

— Outside 2000 km/s the gas has $f \simeq 1$ and the oxygen relative abundance is quite low: O/H$\simeq 5 \times 10^{-5}$, indicating that only the pre-SN oxygen is fluorescently coupled with hydrogen.

— In the inner regions, on the contrary, the O/H 'fluorescent abundance' is large ($\simeq 10^{-3}$) indicating that the hydrogen and oxygen rich clumps are tightly packed together with $\approx 1\%$ of the freshly synthesized oxygen lying within a Sobolev radius from the hydrogen clumps.

A plausible scenario which could explain these results is the following. Immediately after the explosion, the inner, metal rich regions of SN1987A are fragmented by dynamical instabilities and expelled at velocities $v \leq 2000$ km/s inside the hydrogen rich envelope. In the following days the fragments of nickel are inflated by the fast radioactive decay of ^{56}Ni (Li et al. 1993) and compress the hydrogen rich gas inside 2000 km/s; while outside they overshoot and push forward, but do not compress significantly the pre-existing gas, which therefore remains with $f \simeq 1$ and has no scale mixing between hydrogen and oxygen.

Observations of the O I λ11287 line in other type II supernovae are of interest to verify if such a scenario is typical of these objects. The measurements required are medium–high resolution spectra of λ11287 and Brγ to follow the evolution of their profiles and fluxes from the beginning of the super–nebular phase (when the envelope becomes optically thin in the continuum) till the disappearance of the O I line.

1. Introduction

The large amount of observational data available for SN1987A has demonstrated that its envelope is nothing like the simple minded 'onion' which was often considered as a reasonable representation of a type II supernova. The most direct argument comes from the analysis of the profiles of the lines observed after the beginning of the so called super–nebular phase, i.e. after the envelope continuum becomes optically thin (in SN1987A this

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occurs about 150 days after the explosion). In the freely expanding envelope the radial velocity of a given region is strictly proportional to its distance from the center (i.e. the flow is Hubble-like) and the velocity profile of the lines is directly connected to the radial distribution of the emitting gas. An 'onion' with superposed Fe, Si, O, He, H layers should produce narrow [Fe] lines and broader and flat-top [O] and hydrogen lines. The fact that infrared and optical [Fe], [Ni], [O], [Si], H lines have all similar widths is a direct evidence that these elements have similar radial distribution, i.e. are mixed, at least on macroscopic scales.

Several arguments indicate that the mixing is not on microscopic scales. The one I personally prefer is based on the observations of [Fe I] (1.44 μm) and [Ni I] (3.12 μm), from which one derives that, at $\approx$ 400 days, roughly half of the iron and nickel is neutral but is hot enough to emit these lines. This situation is possible only if the Fe/Ni regions are not in chemical contact with the hydrogen (and proton) rich gas as Fe^{o} and Ni^{o} would be quickly ionized by charge exchange with H^{+}.

The analysis of [O I] and Ca II lines suggests that the oxygen- and hydrogen-rich gas is clumped with filling factor $f \sim 0.1$ while the low opacities of the infrared [Fe], [Co] and [Ni] lines indicate that most of the envelope is occupied by low density, iron rich gas (Li and McCray 1992, 1993, Li et al. 1993). An up-to-date picture of the envelope could be that of a Co-Fe 'foam', which fills most of the volume available, with dense clumps of hydrogen, oxygen and other materials more or less uniformly distributed throughout the envelope (see e.g. McCray 1993). In this scenario the radial stratification originally present in the progenitor is forgotten and one does not expect large differences in the profiles of the various lines.

The O I λ11287 line does not seem to fit in this picture as it is much narrower ($\Delta v \leq$ 2000 km/s) than the other lines from the ejecta. This observation implies that some sort of radial stratification must exist in the envelope. What is the difference between the gas inside and outside 2000 km/s? More generally, does the O I line fit at all in the above scheme and, if so, what can one learn from it?

The answers to the above questions can be found in a long paper recently published in Astronomy & Astrophysics (Oliva 1993). This communication is intended to give a quick overview of the modeling procedure and results, and to emphasize the importance of the O I line as a diagnostic tool for the study of hydrogen rich supernovae.

2. Basic model features

Supernova envelopes are dense, cool and very opaque in emission lines. These unusual conditions are often outside the limits of the 'classical' works dealing with line formation. This is particularly true for the O I line where a blind application of the handy theory developed, among the others, by Grandi (1980) makes one predicting that the ratio I(λ11287)/I(Brγ) should rapidly fade with time following the decrease of Hα opacity ($\approx t^{-4}$) while the observed ratio *increases* by almost a factor of 2 between 200 and 400 days. The discrepancy is resolved by including the effect of transfer in the oxygen lines produced by the Lyβ fluorescence (Fig. 1). Using very reasonable approximations one finds that when λ11287 is opaque (which is the case at early times) the relative intensity of λ11287 does not depend on the O/H relative abundance and is solely determined by the opacities of Hα and Lyα:

$$I(\lambda 11287)/I(\mathrm{Br}\gamma) \propto [\tau(\mathrm{H}\alpha)\,\tau(\mathrm{Ly}\alpha)]^{-1/3} \qquad (2.1)$$

and increases with t_{SN} as the opacities of Hα and Lyα are both decreasing with time.

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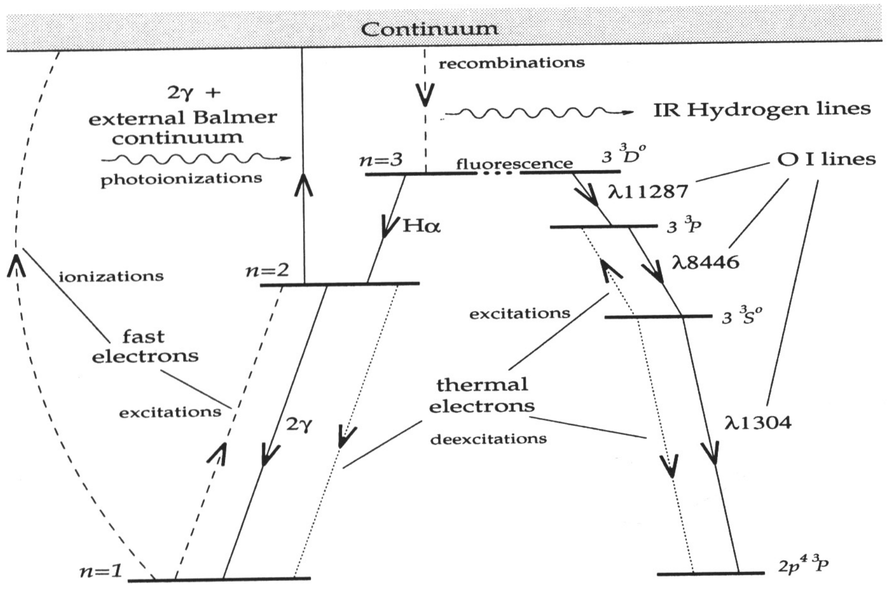

FIGURE 1. Schematic representation of the most important processes involved in the production of λ11287

Once λ11287 becomes transparent its relative intensity is given by the classical relationship:

$$I(\lambda 11287)/I(\mathrm{Br}\gamma) \propto \mathrm{O/H}\,[\tau(\mathrm{H}\alpha)]^{-1} \tag{2.2}$$

and fades with t_{SN} following the decrease of Hα opacity. Therefore, the peak of the λ11287/Brγ 'light curve' marks the time at which the optical depth of λ11287 approaches unity.

The network of processes which must be taken into account for the modeling of λ11287 is sketched in Fig. 1. Basically, one must considered an 'extended' hydrogen atom including the oxygen levels populated by fluorescence. The method for the determination of the hydrogen levels population is that described by Xu et al. (1992) while the oxygen levels are treated in Oliva (1993). The modeling procedure can be outlined as follows.
— The hydrogen recombination rate is given by the observed intensities of IR hydrogen lines
— The above parameter sets the opacities of hydrogen lines once the filling factor f – the first free parameter of the model – is given, the lower the value of f the thicker the lines.
— The second free parameter is the O/H resonant abundance which sets the efficiency of Lyβ fluorescence.

The effect of varying f and O/H can be visualized in Fig. 2 which shows λ11287/Brγ theoretical light curves for several combination of parameters. The two parameters have distinct effects: f determines the time at which the peak occurs (lower f values make the envelope thicker so that λ11287 becomes transparent at later times) while O/H primarily determines the amplitude of the peak. Therefore, one has good chances to independently constrain the values of f and O/H. For simplicity I avoid discussing here the effect of the external Balmer-ionizing field ($\xi_{2,C}$, Xu et al. 1992), which is a 'disturbing' parameter which also influences the amplitude of the peak but has minor effects on the final results.

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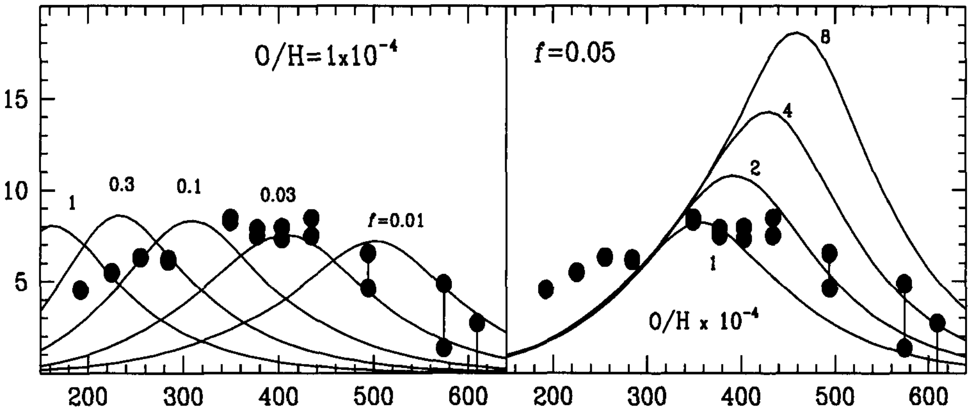

FIGURE 2. Comparison between the observed evolution of O Iλ11287/Brγ (filled circles) and theoretical 'light curves'. The left panel shows the effect of varying the filling factor f while the effect of O/H is displayed in the right hand panel.

3. Results

The only direct result which can be derived by comparing observed and theoretical light curves (Fig. 2) is that the hydrogen-rich gas that pumps the observed O Iλ11287 must be clumped with $f \approx 0.03-0.1$, and this fits well in the current view of the SN1987A envelope. All the other results, namely O/H abundance and radial stratification of the physical conditions, derive from the analysis of the line profile. The observed width of λ11287 is FWHM $\leq$2000 km/s, much narrower than Brγ and any other line, and its profile did not vary significantly from day 200 to beyond day 400 (Fig. 3). This last fact implies that there is no important radial stratification (i.e. variation of physical conditions with radius) of the clumps in the central 2000 km/s. To better understand this, assume for example that the densest hydrogen rich material – i.e. that with the lowest filling factor – is concentrated within a smaller radius (1000 km/s, say). These clumps would dominate the emission at late epochs and the line would narrow with time, in disagreement with the observations.

An analysis of Brγ and λ11287 profiles indicates that roughly half of the hydrogen recombinations occur outside 2000 km/s where the λ11287/Brγ ratio is a factor $>$ 6 lower than inside. What makes the gas outside 2000 km/s a much less efficient O I emitter? There are two possibilities:

— The gas has a lower filling factor, it reaches its O I peak very early and fades before 200 days (time of the first reliable measurements of λ11287).

— The gas has a lower O/H resonant abundance, and never produces significant λ11287.

From Fig. 2 one can easily realize that the first effect is not enough: the least dense component ($f = 1$) peaks just before 200 days and at this epoch the O I line was already narrow (Fig. 3). One therefore requires a variation of O/H which must be large because the amplitude of the λ11287/Brγ peak is a slow function of O/H ($\approx$[O/H]$^{1/3}$). One can easily demonstrate (sect. 3.6 of Oliva 1993) that the gas outside 2000 km/s must have an oxygen abundance at least a factor of 20(!) lower than inside. Is this compatible with our view of SN1987A? At first sight a radial variation of O/H seems unreasonable for the following reasons:

— The value of O/H derived from λ11287 is the oxygen relative abundance averaged over a Sobolev length ($\approx$ a thousandth of the SN size), the maximum distance over which fluorescence can work. Several evidences indicate that the mixing in SN1987A was quite

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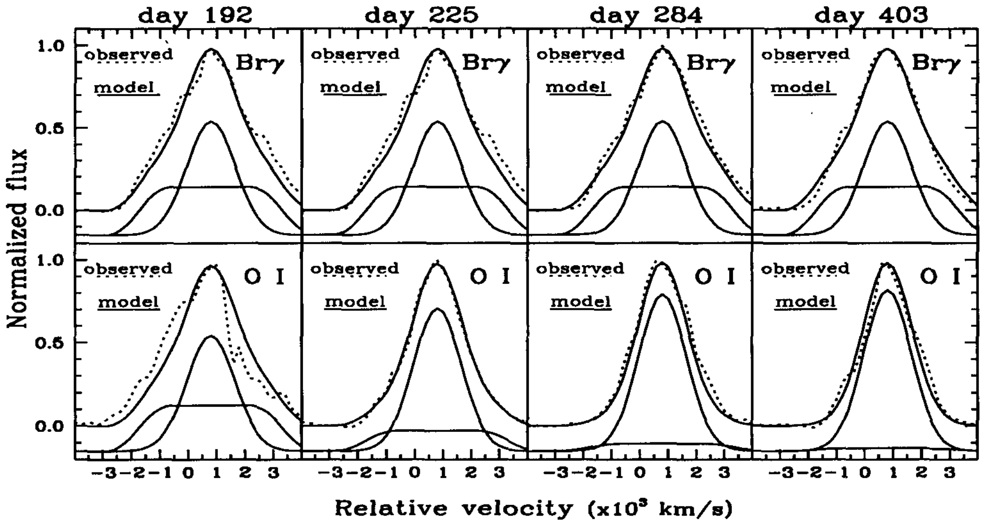

FIGURE 3. The dashed lines are the observed profiles of λ11287 and Brγ at various epochs. The results from a model with a strong radial stratification of O/H (1×10^{-3} inside 2000 km/s and 5×10^{-5} outside) are given as solid lines. The relative contribution of the inner (Gaussian profile) and outer (flat top profile) regions are also shown. See Oliva (1993) for more details.

rough and it is not at all clear if it could work on so small scales.
— From [O I]λ6300 we know that the freshly synthesized oxygen extends to at least 2500 km/s. What is the process which produced small scale mixing inside 2000 km/s but not outside?

A possible explanation is along the line of the 'inflating–Ni–clumps' model of Li et al. (1993, see also McCray 1993). In the first days after the explosion the fragments of the nickel bubble are inflated by the rapid decay of ^{56}Ni and rapidly occupy most of the space available. All the other material in the ejecta is either compressed in between the Co-Fe balloons or pushed aside, the latter occurring in the outermost regions. If the original nickel fragments were mostly concentrated inside 2000 km/s one expects that the Ni 'balloons' overshoot into the outer region without significantly compressing the pre-existing gas, while all the material within the above radius is squeezed by different amounts. Hence, the width of the oxygen line is a direct measurement of the volume originally occupied by the nickel fragments before inflation.

The λ11287 modeling requires O/H$\sim 1 \times 10^{-3}$ hence the mass of 'fluorescently–mixed' oxygen is $M_{mixed}(O) \sim 0.016\, M_{2000}(H)$, $M_{2000}(H)$ being the hydrogen mass in the inner 2000 km/s which can be estimated as follows. To match the observed luminosities of hydrogen recombination lines one requires that $\sim 1\ M_\odot$ of hydrogen is exposed to ^{56}Co decay (Xu et al. 1992). Roughly half of the hydrogen lines are emitted from the central 2000 km/s (Fig. 3), hence $M_{2000}(H) \sim 0.5\ M_\odot$ and $M_{mixed}(O) \sim 0.01$. One therefore requires that roughly 1% of the freshly synthesized oxygen† is mixed with hydrogen on scales smaller than a thousandth of the SN size. Such a fine mixing can be better achieved if the hydrogen and oxygen clumps have a filamentary shape, it would be of interest to verify if the pressure from the inflating Ni 'balloons' is enough to produce filaments so closely packed together.

A last, interesting result concerns the pre-SN oxygen abundance. In the region outside

† The fraction quoted in Oliva (1993, 10%) is wrong as it was computed assuming a too large hydrogen mass ($M_{2000}(H) = 5$), I apologize to the readers for this error.

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2000 km/s a very low oxygen abundance is needed to keep the λ11287 emission below the observed upper limit: $O/H \leq 5 \times 10^{-5}$. This indicates that the progenitor of SN1987A had a O/H much smaller than other blue stars in the field. The above value is a factor 1.8 lower than that used to model the spectrum of the ring (Lundqvist & Fransson 1991). It would be of interest to verify if this difference is really significant.

4. Future Observations of Supernovae.

Since the O I λ11287 line is formed by Lyβ fluorescence, it is reasonable to expect that it should be bright in all hydrogen–rich supernovae. The modeling of λ11287 requires a hydrogen recombination line for reference. The best one is probably Brγ, as it is relatively isolated and its emission coefficient is insensitive to the opacity of the gas (Xu et al. 1992). The light curve of λ11287/Brγ, and in particular the position of its peak, can be used to derive the filling factor of the hydrogen rich gas. The most interesting measurement would be that of the O I and Brγ line profiles: finding a narrower O I would be a trace of the 'Ni–inflation'. The main advantage of using λ11287 rather than middle IR lines of [Fe] and [Co] – which can give a more direct check of this theory – is observational: at 1.13 μm one can measure distant objects while observations at $\lambda > 10$ μm are possible only for bright and nearby supernovae. There is a potential limitation for the use of the λ11287 profile: in SN1987A the narrowing of λ11287 is pronounced because the oxygen abundance outside 2000 km/s is quite low, if the supernova progenitor was oxygen rich (or even with cosmic oxygen abundance) it may happen that the mixing in the inner regions does not produce a large increase of O/H. However, even a small O/H contrast should be recognizable by following the time evolution of λ11287 and Brγ profiles, the first should narrow with time.

In conclusion, the oxygen line can give interesting information on the physics of the envelopes of hydrogen rich supernovae. The observations required are medium–high resolution ($\leq$ 300 km/s), high S/N spectra of λ11287 and Brγ from the beginning of the supernebular phase till as late as possible (ideally till the O I line disappears).

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