The circumstellar medium of the peculiar supernova SN1997ab.*

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\textbf{ABSTRACT}

We report the detection of the slow moving wind into which the compact supernova remnant SN 1997ab is expanding. Echelle spectroscopy provides clear evidence for a wellresolved narrow (Full Width at Zero Intensity, FWZI \(\sim \) 180 km s\(^{-1}\)) P-Cygni profile, both in H\(\alpha\) and H\(\beta\), superimposed on the broad emission lines of this compact supernova remnant. From theoretical arguments we know that the broad and strong emission lines imply a circumstellar density \((n \geq 10^7 \text{ cm}^{-3})\). This, together with our detection, implies a massive and slow stellar wind experienced by the progenitor star shortly prior to the explosion.

\textbf{Key words:} Supernovae and Supernova Remnants: general - Supernovae and Supernova Remnants: SN 1997ab - Circumstellar Medium.

* Based on observations made with the 4.2-m WHT operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.
1 INTRODUCTION

SN1997ab, like SN1987F or SN1988Z (Filippenko 1989, Turatto et al. 1993) is a peculiar type II supernova (SN) with a luminosity of $M_B = -17.5$ one year after its discovery (Hagen, Engels & Reimers 1997). It was first detected on April 11, 1996, in the dwarf galaxy HS 0948+2018, far from the galaxy center, showing broad Balmer emission lines, FWHM $\sim 2500$ to $3000$ km s$^{-1}$, without the typical P-Cygni profiles of type II SN. The redshift derived from the narrow emission lines seen in SN 1997ab is 0.012 (Hagen et al. 1997). These peculiar SN, also called “Seyfert 1 impostors” (Filippenko 1989), given their profound resemblance to the emission spectra from Seyfert 1 nuclei, are sometimes also identified as radio supernovae (RSN; see Van Dyk et al. 1993, 1996). The standard explanation for these sources (Chugai 1990, Terlevich et al. 1992, 1995) demands the expansion of a supernova shock into a dense circumstellar medium, and thus it is believed that what we see is the SN remnant and not the SN itself. Indeed, the release of $10^{51}$ erg into a high density medium ($\geq 10^6$ cm$^{-3}$) is known to lead to a rapidly evolving remnant, which skips its quasi-adiabatic Sedov evolutionary phase to become strongly radiative, reaching luminosities $\geq 10^9$ L$_\odot$ even before the ejecta is fully thermalized at the reverse shock (see Wheeler et al. 1980; Terlevich et al. 1992). The rapid evolution is a direct consequence of the high densities, which promote the earlier onset of strong radiative cooling in the matter swept up and strongly accelerated by the blast wave. Strong cooling causes the collapse of the swept up gas into a thin shell while still moving at several thousands of km s$^{-1}$ and with it, to an outburst of radiation capable of ionizing the cooling shell, the unshocked ejecta and the background gas. In this way the supernova energy, the $10^{51}$ erg originally released as kinetic energy, is radiated away in just a matter of a few years. This causes the most luminous SN remnants, although they only acquire sizes $\sim$ a few $10^{16}$ cm, and hence have been termed “compact” supernova remnants (CSNRs).

Here we provide unambiguous evidence for the existence of a slowly expanding, dense circumstellar medium around SN 1997ab and work out its relevant physical properties.

2 THE OBSERVATIONS

On May 30 1997, the supernova remnant, SN1997ab (Hagen et al. 1997), was observed with the Utrecht Echelle spectrograph at the 4.2-m William Herschel Telescope at the “Roque de los Muchachos” observatory (La Palma, Spain). A 1200s exposure of the supernova remnant
was obtained using a 2148×2148 Tek CCD and the 79.0 lines/mm echelle, reaching a S/N ∼ 30 at Hα. The orders covered are 45 to 30, from ∼ 4130 Å- 7340 Å, including Hβ and Hα. The spectral resolution of our setup was 0.13 Å in the Hβ region and 0.18 Å in the Hα region. This led to a resolution of ∼ 8 km s⁻¹. The CCD frames were reduced using standard procedures with the tasks in IRAF. The data was debiased, trimmed and flat-field using a normalized flat field produced with apflatten. The spectra were extracted using doecslit with appropriate parameters. Wavelength calibration was performed by using the comparison spectrum of Thorium-Argon arcs. Flux calibration was accomplished through the observation of standard stars. The atmospheric extinction correction was also applied at the time of calibration using the mean extinction curve for La Palma. No redshift correction was applied, and therefore the wavelengths are the observed ones, unless otherwise stated. The seeing was less than 1.5 arc seconds.

2.1 Line analysis

Figure 1 shows the spectral regions around Hα and Hβ lines. Both of these lines have two components: a broad component with a FWHM ∼ 1800 km s⁻¹ and a narrow (FWZI ∼ 180 km s⁻¹) P-Cygni profile superimposed on the broad lines. Note that the broad components present a flat-topped profile, typical of expanding shells, and that the P-Cygni narrow lines are somewhat displaced towards longer wavelengths. The broad lines indicate a large expansion velocity of (at least) ∼ 2000 to 4000 km s⁻¹, as measured from their red and blue wings, respectively. However, the fact that the P-Cygni profiles are shifted implies that the red part of the broad components of both, Hα and Hβ, are probably self-absorbed and therefore missing. As a consequence, the intrinsic true width of the broad profiles could be almost twice as large as what one can at first glance measure. Also, given the small wavelength range covered in each portion of our spectra, the broad Hα and Hβ lines are not fully sampled and their wings and adjacent continuum are missing. Therefore, regardless of their asymmetry, the FWZI cannot be measured in our Echelle spectra. A better determination of the FWZI is to be found in previous published (low-dispersion) spectra of this CSNR (Hagen et al. 1997, Salamanca et al. 1998) which indicates a velocity of ∼ 6600 km s⁻¹.

The narrow P-Cygni lines shown in Figure 1 on top of the broad Hα and Hβ, must arise in a medium with a much smaller velocity, $v_w ∼ 90$ km s⁻¹, as deduced from their half width at zero intensity.
Figure 1. The Hβ and Hα profiles of SN1997ab. The flux is in units of erg Å⁻¹ s⁻¹ cm⁻². A “smooth” has been applied to both spectra to reduce the noise in the wings.
3 DISCUSSION

The detection of narrow P-Cygni profiles in H\(\alpha\) and H\(\beta\), superimposed on the broad emission lines produced by the compact supernova remnant SN 1997ab, proves the existence of a slowly expanding, dense medium into which the CSNR shock evolves. From the analysis of the broad lines one can derive the physical conditions of the SN ejecta and its main shock. On the other hand, the narrow P-Cygni lines tell us about the density and extent of the CSM. One word of warning however: some of the narrow Balmer emission is contaminated by the extended emission from the host galaxy, a starburst galaxy of low excitation. Nevertheless, the emission coming from the host galaxy is very weak, and therefore its contamination is negligible in a first approximation. More detailed analysis will be referred to upcoming publications (Salamanca et al. 1998).

To estimate the density and extent of the envelope, we assumed that the wind from the progenitor star that created it is freely expanding with a velocity, \(v_w\). The density (\(\rho\)) of the slow wind then falls as \(r^{-2}\), under the assumption of a constant mass-loss rate, \(\dot{M}\),

\[
\dot{M} = 4\pi r^2 v_w \rho
\]

3.1 The broad lines and the CSNR shock

When the shock in the circumstellar medium is the dominant source of luminosity, rather than the release and escape of stored radioactive energy, then the luminosity in the broad H\(\alpha\) line is simply proportional to the kinetic energy dissipated per unit time across the shock front (Terlevich 1994, Chugai 1991),

\[
L_{\text{Broad}} = \frac{1}{2} \dot{M}_{CSM} v_s^2,
\]

where \(v_s\) is the shock velocity and \(\dot{M}_{CSM} = \frac{\dot{M}}{v_w} v_s\) is the rate at which the circumstellar medium (CSM) is swept up. The \(r^{-2}\) density distribution will ensure that the shock velocity can be regarded as constant (until an appreciable fraction of the kinetic energy is radiated away). This leads to

\[
L_{H\alpha}^{\text{Broad}} = \frac{1}{4} \epsilon_{H\alpha} \frac{\dot{M}}{v_w} v_s^3
\]

where we have taken into account the fact that only half of the radiation from the gas cooling behind the shock will contribute to the ionization of the shell, while the other half will be transported outwards. The value of the efficiency factor \(\epsilon_{H\alpha}\), depends on the time elapsed since the explosion of the supernova, and ranges from a maximum value \(\sim 0.1\) when
catastrophic cooling starts, and then steadily drops to nearly zero within the evolutionary
time of the CSNR (Terlevich 1994 and Cid-Fernandes & Terlevich 1994).

In the case of SN 1997ab, \( v_s \) and \( v_w \) are easy to determine from the FWZI of the broad
and narrow lines, respectively: \( v_s \) is about \( \sim 6600 \text{ km s}^{-1} \) and for \( v_w \) we shall adopt a
value of \( 90 \text{ km s}^{-1} \) (see previous section). The luminosity in H\( \alpha \) is \( \sim 5 \times 10^{41} \text{ erg s}^{-1} \). This
value, taken from Hagen et al. (1997), is probably a lower limit, since we did not take into
account reddening or obscuration effects. The value of \( \epsilon_{H\alpha} \) is directly related to the Balmer
decrement, since it depends essentially on the density of the CSM. From previous spectra
of SN 1997ab (Hagen et al. 1997) we have \( \frac{H\alpha}{H\beta} \sim 6 \) which led us to the conclusion that \( \epsilon_{H\alpha} \)
must be \( \sim 0.1 \) (see also Terlevich 1994). Note also that, as SN 1997ab was not seen on April
5th 1995 (Hagen et al. 1997), then an upper limit to the time elapsed since the explosion up
to the end of May 1997, is 783 days, which is again consistent with large values of \( \epsilon_{H\alpha} \).

The values of \( v_s, v_w, L_{H\alpha}, \) etc. have been obtained from spectra taken at epochs separated
by 1 to 3 months. However, we regard this as a valid approximation as these objects fade
very slowly.

Substituting these values into equation 2 we obtain a mass-loss rate \( \dot{M} \) (for \( \epsilon_{H\alpha} = 0.1 \))
\( \sim 10^{-2} \, \text{M}_\odot \text{yr}^{-1} \), which in what follows is used as reference value.

The radius of the shock, or inner radius \( (R_i) \) of the unshocked CSM able to produce the
narrow P-Cygni profile, can be expressed as a function of the local density. From equations 1
and 2 we have:

\[
R_i = 1.54 \times 10^{16} \left[ \frac{(\dot{M}/10^{-2} \text{M}_\odot \text{yr}^{-1})}{(v_w/90 \text{ km s}^{-1})} \right]^{1/2} \frac{1}{\frac{n_i}{10^7 \text{cm}^{-3}}} \, \text{cm} \quad (4)
\]

\[
R_i = 1.54 \times 10^{16} \left[ \frac{L_{H\alpha}/5 \times 10^{41} \text{erg s}^{-1}}{(n_i/10^7 \text{cm}^{-3})} \right]^{1/2} \frac{1}{\frac{v_s}{6.6 \times 10^8 \text{cm s}^{-1}}} \, \text{cm} \quad (5)
\]

where \( n_i \) is the density of H atoms at \( R_i \) and \( \rho = 1.4 n_H m_H \) (accounting for a 10\% He abundance by number).

### 3.2 Narrow P-Cygni lines and the CSM

We use the luminosities of the emission narrow Balmer lines to estimate the unshocked mass
and outer radius of the CSM. These are given by:

\[
L_{\text{Balmer}}^{\text{narrow}} = \int_{R_i}^{R_o} 4\pi r^2 n^2 \alpha_B h\nu_\delta dr \quad (6)
\]

were \( \alpha_B \) is the case B recombination coefficient and we have supposed that the CSM emits
isotropically and that it is fully ionized.
For this estimation we use either the luminosity of the narrow H\(\alpha\) or H\(\beta\) lines: The H\(\alpha\) line is more intense and it therefore has a better signal-to-noise ratio, but in many cases it may be enhanced by collisions and therefore, the above relation (8) would no longer be valid. The H\(\beta\) line is not affected by collisional effects, but it is by reddening. The ratio H\(\alpha\)/H\(\beta\) is \(\sim 20\), which suggests a high density medium, \(n \sim 10^8 - 10^{10}\), for an ionization parameter \(\log U = -2\) and \(-4\) respectively. In what follows we will use the observed values of the luminosities in H\(\alpha\) and H\(\beta\) narrow emission lines. They will give us an upper and lower limit respectively to the density and extent of the CSM.

The integration of the above equation using \(n = n_i(r/R_i)^{-2}\), yields

\[
L_{\text{Balmer}}^{\text{narrow}} = \frac{\alpha_B \hbar \nu_o}{2\pi^{1/2}(1.4m_H)^{3/2}} \left(\frac{\dot{M}}{v_w}\right)^{3/2} n_i^{1/2} \left(1 - \frac{R_i}{R_o}\right) \quad (7)
\]

\[
= 3.05 \times 10^{37} \alpha_B \nu_o \left[\left(\frac{\dot{M}}{10^{-2} M_\odot \, \text{yr}^{-1}}\right)\right]^{3/2} \left(\frac{n_i}{10^7 \text{cm}^{-3}}\right)^{1/2} \left(1 - \frac{R_i}{R_o}\right) \text{ erg s}^{-1} \quad (8)
\]

Using the relationship between \(\dot{M}\) and \(L^{\text{Broad}}_{H\alpha}\) (see equation 2) one gets:

\[
L_{\text{Balmer}}^{\text{narrow}} = \frac{4\alpha_B \hbar \nu_o}{\pi^{1/2}(1.4m_H\epsilon_{H\alpha})^{3/2}} \left(\frac{L^{\text{Broad}}_{H\alpha}}{v_s^3}\right)^{3/2} n_i^{1/2} \left(1 - \frac{R_i}{R_o}\right) \quad (9)
\]

\[
= 3.05 \times 10^{37} \alpha_B \nu_o \left[\left(\frac{L^{\text{Broad}}_{H\alpha}}{5 \times 10^{41} \text{ erg s}^{-1}}\right)\right]^{3/2} \left(\frac{n_i}{10^7 \text{cm}^{-3}}\right)^{1/2} \left(1 - \frac{R_i}{R_o}\right) \text{ erg\(\text{s}\)}^{-1} \quad (10)
\]

Substituting the appropriate values for the \(L^{\text{narrow}}_{H\alpha}\) or \(L^{\text{narrow}}_{H\beta}\) and \(\alpha_B\) and \(\nu_o\) we estimated the value of the outer CSM radius, \(R_o\), as a function of the density \(n_i\) at the inner edge \(R_i\) of the CSM. The observed value of \(L^{\text{narrow}}_{H\alpha}\) is \(4 \times 10^{39}\) erg s\(^{-1}\) and of \(L^{\text{narrow}}_{H\beta}\) \(2 \times 10^{38}\) erg s\(^{-1}\) \((H_0 = 75 \text{ km s}^{-1} \text{Mpc}^{-1})\). The true value must be certainly larger, since the blue side of the line is in absorption. To account for this and possible obscuration effects we have multiplied the observed emission luminosities by a factor of 2. The values of \(\alpha_B\) taken are: \(\alpha_{H\alpha} = 2.59 \times 10^{-13}\) cm\(^{-3}\) s\(^{-1}\) and \(\alpha_{H\beta} = 3.07 \times 10^{-14}\) cm\(^{-3}\) s\(^{-1}\) (Osterbrock 1989).

To explain the observed narrow H\(\beta\) emission, the CSM must have a minimum mass, and this imposes a natural lower bound on \(n_i\):

\[
n_i \geq 3 \times 10^5 \text{ cm}^{-3} \left(\frac{L^{\text{narrow}}_{H\beta}}{10^{38} \text{ erg} \, \text{s}^{-1}}\right)^2 \left[\left(\frac{\dot{M}}{10^{-2} M_\odot \, \text{yr}^{-1}}\right)\right]^{-3} \quad (11)
\]

and thus, a less dense CSM could not produce the observed H\(\beta\)\(^{\text{narrow}}\) line. This relationship is valid for an infinite CSM. For a finite medium, the density must be even larger.

Tables 1 and 2 lists the values of \(R_i, R_o\), the density \((n_o)\) at \(R_o\), as well as the mass of the swept up CSM (up to \(r = R_i\)) and of unshocked CSM mass (from \(R_i\) to \(R_o\)) for different
Table 1. CSM values inferred from the H\textsubscript{narrow} line

| $n_i$ cm$^{-3}$ | $R_i$ cm | $R_o$ cm | $n_o$ cm$^{-3}$ | $\Delta R$ cm | $M_{CSM}$\textsubscript{shocked} M$_\odot$ | $M_{CSM}$\textsubscript{unshocked} M$_\odot$ | $t_{\text{wind}}$ years | $t_{SN}$ years |
|----------------|----------|----------|----------------|--------------|-----------------|-----------------|----------------|-------------|
| $5 \times 10^7$ | $6.9 \times 10^{15}$ | $5.0 \times 10^{17}$ | $6.8 \times 10^3$ | $5.8 \times 10^{17}$ | 0.24            | 20.4            | 2080           | 0.22        |
| $10^8$         | $4.9 \times 10^{15}$ | $7.0 \times 10^{15}$ | $4.9 \times 10^7$ | $2.1 \times 10^{15}$ | 0.17            | 0.07            | 25             | 0.15        |
| $10^9$         | $1.5 \times 10^{15}$ | $2.0 \times 10^{15}$ | $6.1 \times 10^8$ | $5.0 \times 10^{14}$ | 0.05            | 0.02            | 7              | 0.05        |

Table 2. CSM values inferred from the H\textsubscript{narrow} line

| $n_i$ cm$^{-3}$ | $R_i$ cm | $R_o$ cm | $n_o$ cm$^{-3}$ | $\Delta R$ cm | $M_{CSM}$\textsubscript{shocked} M$_\odot$ | $M_{CSM}$\textsubscript{unshocked} M$_\odot$ | $t_{\text{wind}}$ years | $t_{SN}$ years |
|----------------|----------|----------|----------------|--------------|-----------------|-----------------|----------------|-------------|
| $10^7$         | $1.5 \times 10^{16}$ | $5.0 \times 10^{16}$ | $9.6 \times 10^2$ | $3.5 \times 10^{16}$ | 0.5             | 1.2             | 175            | 0.5         |
| $5 \times 10^7$ | $6.9 \times 10^{15}$ | $1.0 \times 10^{16}$ | $2.4 \times 10^7$ | $3.1 \times 10^{15}$ | 0.2             | 0.1             | 35             | 0.22        |
| $10^8$         | $4.9 \times 10^{15}$ | $7.0 \times 10^{15}$ | $6.1 \times 10^7$ | $2.1 \times 10^{15}$ | 0.2             | 0.05            | 22             | 0.15        |
| $10^9$         | $1.5 \times 10^{15}$ | $2.0 \times 10^{15}$ | $8.7 \times 10^8$ | $4.6 \times 10^{14}$ | 0.05            | 0.004           | 6              | 0.05        |

values of $n_i$. We as well list the values of the duration of the progenitor wind, $t_{\text{wind}} = R_o / 90$ km s$^{-1}$, and the time for the supernova shock to reach the inner radius, $t_{SN} = R_i / 10000$ km s$^{-1}$, if assumed to travel at 10000 km s$^{-1}$.

Note that the results for both lines agree only for high densities ($\sim 10^8$ cm$^{-3}$ or bigger), as we would expect from the high value of $H_\alpha$/$H_\beta$ (see previous section). For such high densities, the extent of the CSM becomes extremely small, and the density decreases less than one order of magnitude only. This would imply also that the wind that created such CSM was of very short duration and that the supernova shock reached it on very short times scales (less than two months). However, in the derivation of all these parameters, we have assumed that the narrow Balmer emission lines are due only to recombination effects, and we did not take into account any collisional effects. With the available data we cannot constrain any further these parameters. We need more observations to monitor the narrow P-Cygni profile, since its disappearance will indicate the end of the dense CSM. The numbers presented in tables 1 and 2 must be regarded therefore as an indication of the possible range of values. Note finally that SN 1997ab was not detected in X-rays by ROSAT (A. Fabian, private communication), in agreement with the presence of a very large column density of neutral material surrounding the SN, and thus a massive wind.

The rapidly evolving supernova remnant is a peculiar emitting source, in the sense that all of its radiation arises from matter at very high speeds (several thousands of km s$^{-1}$). This, irrespectively of how dense the circumstellar medium may be, can only be absorbed by a medium between the source and the observer moving with a similar velocity. On the other hand, the P-Cygni profile results from the emission caused by the precursor radiation ahead.
of the blast wave, combined with the absorption due to screening of the radiative supernova remnant shell and the photoionized freely expanding ejecta. From this it follows that a sector of the circumstellar medium, a broad rim, overlapping with the section of the high velocity shell that expands near the plane of the sky and/or with the photoionized freely expanding ejecta also moving near the plane of the sky, is the sector that can absorb it and provoke the P-Cygni profiles here shown. In this respect, the P-Cygni profiles of SN 1997ab are very different to those caused by a wind in front of a standing source (e.g. Rublev 1960, Kuan & Kuhi 1975). A complete fit to the emission profiles is now in preparation (Cid-Fernandes et al. 1998).

The fact that both the emission and absorption P-Cygni profiles are so similar confirms also the fact that the absorbing CSM rim is in fact very broad, and it probably spans from the edge of the expanding cooling shell to the photoionized inner most section of the freely expanding ejecta. In this way also, there is a central neutral ejecta region that must cause the absorption of the redest sections of the broad emission lines.

To our knowledge, a narrow P-Cygni profile atop a broad emission line such as that of SN 1997ab has never been detected in any supernova remnant. Broader P-Cygni profiles (but still narrower than those seen in typical type II SN) have been detected in other peculiar SN, such as SN 1979C (Panagia et al. 1980), SN 1984E (Dopita et al. 1984), SN 1994aj (Benetti et al. 1998) or SN 1996L (Benetti et al. 1996). However, the CSM velocities inferred from the widths of all of these P-Cygni profiles are $\sim 1000 \text{ km s}^{-1}$. If a similar interpretation is given to these lines, then the large values of $v_s$ lead for example in the case of 1994aj to an $M \sim 3.3 \times 10^{-3} \text{ M}_\odot \text{ yr}^{-1}$ and to an $R_i = 1.63 \times 10^{15} \frac{1}{\sqrt{n_i/10^7}}$, i.e. $\sim$ one order smaller than the values deduced for 1997ab. Our result thus broadens the range of values to be expected for the massive winds that occur prior to the explosion.

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† Except maybe in SN 1995G, see IAU Circulars number 6138, 6139 and 6140
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