Coherent spectroscopy of supernova remnant 1987A.

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Abstract

The explanation of the shape and the spectra of SNR1987A becomes easier using coherent interactions between light and matter: Assuming that the present system is close to a Strömgren system, the relatively thin shell lying between the sphere of mainly ionised atomic hydrogen and neutral hydrogen, contains excited atomic hydrogen. It is generally assumed that this medium interacts strongly with light at the eigenfrequencies of the atoms ("on the spot absorptions"). Therefore, having a large column density of excited hydrogen, this medium amplifies so strongly the lines that its superradiance reduces to the emission of Dicke spikes similar to laser emissions. As in a laser, the competition of the modes leaves only a few rays for which the column density of amplifying atoms is maximal; therefore these bright rays are tangent to the inner rim of the shell, observed into a direction as a dotted ring. The emissions of the alpha lines help each other, making induced multiphotonic emissions able to de-excite highly excited atoms or atoms of the continuum corresponding to a collision of a proton and an electron. The very hot, polychromatic light emitted by the star may excite the atoms by a mono or multiphotonic pumping; this absorption combines with the emissions into a multiphotonic induced scattering which amplifies the superradiant beams, so that, in despite of a remaining large radiance, the relatively small star is not anymore visible. Sets of coherent Raman scatterings by recoupling of angular momenta in 2s or 2p atoms of hydrogen, packed in parametric interactions, shift the frequencies of spectra.

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1 Introduction

The aim of this paper is showing that the usual models of the supernova remnant 1987A, without need of light emissions by shock waves, explain fully the observations, provided that the coherence of used light-matter interactions is taken into account. In particular, stimulations strongly multiply emissions and scatterings.

Light and neutrinos from Supernova 1987A arrived at Earth on February 23, 1987 after a 166 000 year trip. Its brightening was very rapid: by a factor 100 in 3 hours, eventually reaching magnitude 2,9 in 80 days. This slow rise, and the slow speed of hydrogen observed in the infrared, show that the mass of hydrogen envelope of the star was of the order of 10 solar masses. Then the magnitude decreased almost linearly to 16 in 1000 days (Arnett et al. [1]). Its initial spectrum was very rich in UV and showed broad hydrogen and helium emission lines. Then the UV decreased and remained only emission lines of low ionisation elements (Woosley et al. [2]). Ground based images of SN1987A showed a weak blob of gas which was resolved as a circumstellar "equatorial ring"(ER) by the ESA Faint Object Camera on Hubble on August 1990. Comparing the time delay between the maximal emissions of the supernova and the ring gave a diameter of the ring: 1.2 light-year (ly). Knowing its angular size, the distance of the supernova was found precisely (Panagia et al. [3]).

In 1994, two larger "outer rings"(OR) were detected; in 1997, bright spots (pearls) appeared on the ER. The evolution of the rings (necklaces), i.e., the existence of the pearls, is now explained using shock waves between matter ejected by the supernova and matter ejected 20 000 years before in a first explosion of a red supergiant star. However, arguments developed for instance by Lloyd et al. [4], such as the complexity of the explanation of the existence of the pearls, of the thinness of the rings, their inner brightness and of the disappearance of the star, let us suggest a simple optical modification of the old explanation, closer to the interpretation of the spectra of planetary nebulae (Plait et al. [5]).

Inside the rings, we follow the photoionisation model developed by Chevalier et al. [6] and Lundqvist et al. [7, 8], but our spectroscopy differs from their on three points:

(i) We suppose that the star remains very hot and bright, emitting in each direction a luminous flux equivalent to the flux received from the necklace.

(ii) We will show that the source of the necklaces cannot be a torus, but is a shell with the same physical and chemical composition. This shell was observed for the ER by photon echoes, so it is probably stabilised and deformed by an increase of the density of the gas due to old ejections of gas by the star.

(iii) The outer rings may correspond to older ejections of gas observed also by photon echoes.

All spheres used in this paper have a common centre O.

2 The supergiant progenitors.

The explosion of the red supergiant progenitor 20 000 years before the observed blue supernova explosion (Panagia et al. [3]), results from a collapse of its core by fusion of the protons of iron nuclei with electrons, fusion resulting from a cooling of this core. It is usually admitted that the second collapse produces a prompt shock, and that the shock wave may propagate outside the star. However, this process works only with a small core (Myra et al. [9]) while the mass of this star is large, at least 20 times the mass of the Sun.

The explosion of the red progenitor of SN 1987A ejected, along a z' axis, external layers of the red supergiant having a third of its mass and a density decreasing with the distances to the supergiant star and to the z' axis. This cloud of gas is mainly made of hydrogen and helium. The bipolar symmetry of the cloud was observed by Wang et al. [10] and deduced by Sugerman et al. [11] from the observation of light echoes.

The present surface of the star, supposed very hot ($T > 10^6$K), may be heated by nuclear reactions or, if the star is now a neutron star, by accretion of the cloud, the neutron star playing the role of the anticathode of an X-rays tube (except for the gravitational acceleration of the particles).

3 State of gas in Strömgren model (figure 1.)

After the blue supernova explosion, the remaining star had the spectrum of a blue star, emitting very broad Lyman lines of H_I and He and a strong continuous spectrum of shorter frequencies (extreme UV). We suppose that after the main supernova glow the surface temperature of the star does not decrease very strongly, so that its spectrum remains mainly made of broad Lyman lines of H_I and extreme UV.

To simplify the explanations, suppose, in a first approximation, that the whole system has a spherical symmetry around a point O. The cooling of the plasma is limited by the absorption of extreme UV

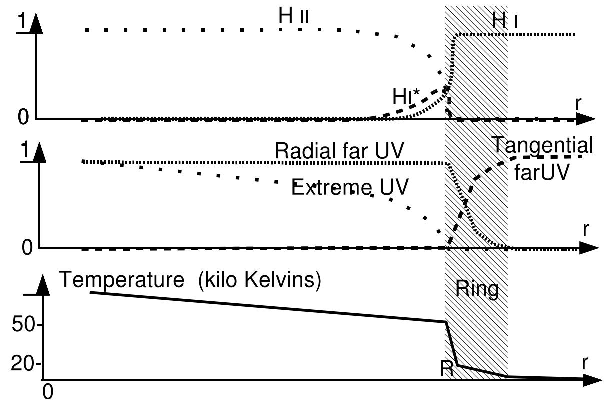

Figure 1: Variation of the relative densities of H_I, H_{II} and excited atomic hydrogen H_I*, relative intensities of light, and temperature along a radius starting at the star.

which ionises generated H_I into electrons and protons (H_{II}), building a spherical bubble of H_{II} inside a cloud of H_I (Chevalier et al. [6]). In the bubble, very few, various ionised atoms (He, C, N, O, ...) absorb energy and radiate their lines. As protons and electrons are nearly free, they do not play a notable optical role.

For a chosen orientation, locate a point by its distance r to the centre O of the star, and set $r = R$ at the inner point of the necklace (figure 1). For r larger than about 3R/4, the remaining intensity in the extreme UV has decreased enough, and the ionisation by several steps is improbable enough, to let appear some H_I, where the temperature of the gas decreases down to around 50 000 K (Arnett et al. [1]). Neutral hydrogen density increases with r. Its Lyman α emission is observed almost constant on the disk inside the ring (Sonneborn et al. [12]), as studied below in subsection 5.2. Strömgren showed that by emitting the lines of atomic hydrogen, these atoms radiate an intense energy, which cools gas and de-ionises new atoms. As this process is self-accelerated it becomes catastrophic for a low proportion of neutral atoms at $r = R$. Cooling is brutal, so that the area where there coexist neutral and ionised atoms constitutes a thin “Strömgren shell” outside of which the gas is made of neutral atoms.

We will show that the radiation process may be much more complex and efficient than thought by Strömgren.

4 Generation of the equatorial ring by a strong superradiance.

4.1 Geometry of the emission.

Recall Einstein theory of emission and absorption [13]:

In a source, variation ΔL of radiance L of a ray at an eigenfrequency of the source ν is almost proportional to the initial brightness of the ray L, to the path Δx, to the difference of the populations of the transition in the states superior (N_U) and inferior (N_L) of the transition of frequency ν, and to a molecular parameter b:

$\Delta L = b(N_U - N_L)L\Delta x$.

At a point, a beam of higher radiance is more amplified (or absorbed) than any other beam, so that for low radiances, the centre of a line being more amplified than the feet, the line is sharpened. For a higher superradiance, the Dicke spike appears at this centre, and for the high superradiance considered in this paper, as in a laser, it remains almost only a strong Dicke spike.

The amplification of a high radiance beam pumps much energy, so that N_U becomes almost equal to N_L. Any other beam is nearly not amplified as much. In this competition of beams (modes), even spontaneous emission is weakened.

More precisely, the radiation temperature deduced from Planck's law tends to equal the transition temperature T_ν deduced from $N_U/N_L = \exp(-h\nu/kT_\nu)$ for the highest radiance beams only. Compare a cylinder cut in Strömgren shell with the gas of a laser tube:

In a gas laser (Helium-Neon, ionised Argon, ...), the number density of active atoms is of the order of 10^{22} m^{-3}, and the length of the active medium, multiplied by the gain of the cavity, of the order of 100 m, so that the efficient number of atoms per unit of surface perpendicular to the light beam (column density) is of the order of 10^{24} m^{-2}. The measured density around the source of the necklace is of the order of 10^{10} m^{-3}, which gives, for paths in H_I of 0.01 light-year, that is 10^{14} m, a column density of 10^{24} m^{-2}. As the efficient column density of excited atoms and the oscillator strengths of their transitions are equivalent, the sources are similar.

The emission of light by the two systems differs only by the selection of longitudinal modes of the laser by its cavity[1]. The same competition of the modes very strongly reduces the number of transverse modes.

[1] As the cavity memorises the phase of emitted light, a CW laser is time-coherent while superradiance, resulting from an amplification of an incoherent emission is not.

As the source is a spherical shell, a ray tangent to the inner sphere of radius R limiting the shell[2] crosses the same regions as a ray coming from inside the shell. The tangent ray has a longer path between two close spheres of centre O, so that it is more amplified for all increases of r. In the competition, it remains only tangent rays. Into a given direction, the bright tangent rays are the generators of a cylinder, seen as a ring. The competition of these rays leaves only spots, as the modes of a laser, and the "pearl necklace" is obtained.

4.2 Spectroscopy of the superradiant beams.

Consider four levels of increasing energies a, b, c, d. If a strong superradiance starts between c and b, it depopulates c and populates b. The higher population b favours a strong superradiance from b to a; the lower population c favours a superradiance from d to c. Thus cascades of transitions, in particular the α transitions, are favoured, along the same path. However, as the limitation of the modes by diffraction is different, the spots will differ, being smaller at shorter wavelengths and closer to the inner limit of the shell. As the emissions are induced by high temperature superradiant beams, they are fast, mixed into multiphotonic emissions which bring fast the atoms from high energy levels to the ground level 1s. Collisional states, included in these high energy states, become non-elastic. In order to reach the eigenstates, the colliding proton and electron perform first low energy, discrete or non-discrete transitions.

Assuming that the superradiant beams cross out of the shell, which is a cold, low pressure gas containing various atoms or molecules, a beam may excite a column of gas whose emission along the axis of the column may be superradiant. The hydrogen emission is completed by sharp lines, as observed.

4.3 Induced scattering of light emitted by the star.

The spectrum of light emitted by the star (radial rays) is made of such broad lines that it is continuous. In each spectral element, its temperature is very high, over 10^6 K. Thus multiphotonic absorptions may occur, pumping the neutral atoms up to ionisation states. But these states are immediately de-excited by the multiphotonic emission described in the previous subsection. This absorption combines

[2] We suppose that it exists column densities large enough for the start of a strong superradiance; for a precise definition, R is defined optically, as the smallest radius (distance from O to the superradiant ray) allowing the superradiance.

with the emission into a parametric interaction of light beams with 1s neutral atoms. These atoms are not excited by this interaction, only dressed by the radial and superradiant beams. As in other parametric interactions (for instance multiplying, combining laser frequencies in crystals), the entropy is increased by a transfer of energy of the very high temperature beam(s) (here radial beams) to lower temperature beams (here superradiant). Almost the whole high temperature continuous spectrum of the radial beams may be transferred to the lines of the superradiant beams whose temperature is lower.

Into a given direction, the radiance of the radial beams tends to the radiance of the beams making the ring. Assuming that the solid angle of observation of the star is much lower than the solid angle of observation of a dot of the ring, the flux received from the star is much lower than the flux received from the dot, so that the star becomes invisible.

The internal rim of the ring is brighter because the radial, exciting rays are less absorbed. As the observed radiances depend on non-linear processes, they are very sensitive to variations of the incident radiances and of the state of gas, which explains, particularly, the appearance of "hot spots".

As a large fraction of the radial flux of energy is transferred tangentially and therefore remains a longer time in the shell between two spheres of centre O, the density of energy is much higher in the Strömgren shell than elsewhere.

5 Frequency shifts.

Excited atomic hydrogen appears in the external regions of the Strömgren sphere. This excited hydrogen radiates the Ly_α line, the emission becoming stronger and stronger with an increase of the radius.

5.1 Can hydrogen atoms scatter light?

Rayleigh theory of scattering shows that the sources of incoherent scattering are fluctuations of density of the gas considered as a perfect gas. Thus, the scattering is proportional to the density of atoms. But the very low pressure gas cannot be considered as making a continuous perfect gas because the collisional time is larger than the duration of the light pulses: the incoherent phaseshifts required for the incoherent scattering are provided mainly by binary collisions whose number is proportional to the square of the density. The decrease of the incoherent scattering if pressure decreases is so fast that incoherent scattering is negligible.

Therefore, only coherent scatterings may occur. Rayleigh coherent scattering is refraction, without spectroscopic result. It is difficult to observe a Raman coherent scattering in a bulk medium because the wavelengths of the exciting and scattered frequencies differ[3], so that the scatterings on successive wave surfaces cancel by interference. However, using short pulses, the spectra of the exciting and scattered light may be broadened enough for an interference. Lamb [14] wrote the conditions: The light pulses must be "shorter than all relevant time constants". For the collisional time, the condition is fulfilled in the very low pressure gas by the pulses of ordinary incoherent light whose length is of the order of a nanosecond. One can show directly that the Raman period must be longer than the length of the pulses:

For a coherent scattering, the wave surfaces are identical for the exciting beam and the scattered beams; therefore, the beams may interfere to produce identical wave surfaces. Set $E_0 \sin(\Omega t)$ the amplitude of the exciting beam and $K\epsilon \sin((\Omega+\omega)t)$ the amplitude scattered with the Raman shift ω between two close wave surfaces distant of ϵ. K is positive for an anti-Stokes scattering. To keep the energy for $\omega = 0$, E_0 must be multiplied by $(1 - K\epsilon)$.

Supposing that a light pulse starts at time $t = 0$, for which the emergent beams are in phase, their sum is:

$$E = E_0[(1 - K\epsilon)\sin(\Omega t) + K\epsilon \sin((\Omega + \omega)t)]$$
$$E = E_0[(1 - K\epsilon)\sin(\Omega t) + K\epsilon \sin(\Omega t)\cos(\omega t) + K\epsilon \sin(\omega t)\cos(\Omega t) \quad (1)$$

Supposing that the length τ of the light pulse is short enough to get $\omega\tau$, therefore ωt, small, and use a valuable first order development of the trigonometric functions:

$$E \approx E_0[\sin(\Omega t) + \sin(K\epsilon\omega t)\cos(\Omega t)]$$
$$E \approx E_0[\sin(\Omega t)\cos(K\epsilon\omega t) + \sin(K\epsilon\omega t)\cos(\Omega t)]$$
$$E \approx E_0 \sin((\Omega + K\epsilon\omega)t) \quad (2)$$

It remains a single frequency, so that the frequency shift adds along the paths of light. The neglected terms cancel by interference, so ωt may increase up to π. Taking into account the Stokes and anti-Stokes scattering, in the best of conditions the frequency shift is proportional to τ^{-3} [15].The relative frequency shift is constant in the approximation which neglects the dispersion of the indices of refraction.

Using femtosecond pulses, the frequency shift in optical fibres used for transmission of data must be taken into account. High power laser

[3]except in crystals used in laser technology.

pulses induce a nonlinearity which increases the effect so much that it may be observed in small cells. The linear effect is named “Coherent Raman Effect on Incoherent Light” (CREIL) while the nonlinear effect is named “Impulsive Stimulated Raman Scattering” (ISRS) (Yan et al. [16], Weiner et al. [17], Dougherty et al. [18], Dhar et al. [19]).

In these coherent effects, matter is “dressed” by the electromagnetic field during the pulses, its state being slightly mixed with other states. The relative frequency shift is constant in the approximation which neglects the dispersion of the indices of refraction. The matter must return to its stationary state after the interaction: the effect is named “parametric”, and there is no permanent change of the energy of matter (happily for the crystal used with lasers). As a Raman interaction exchanges energy, the interaction with a beam must be compensated by at least an exchange with an other beam (first principle of thermodynamics). The light beams have a temperature deduced from their radiance using Planck’s law. The second principle of thermodynamics says that energy must flow from hot to cold, that is, generally, from high frequency beams (light) to low frequency beams (radio, thermal radiation).

The usual, incoherent light is made of nanosecond pulses, 10^5 times longer than the usual femtosecond laser pulses, so that a similar frequency shift requires a 10^{15} times larger path, an astronomical path.

In atomic hydrogen, Raman resonance periods correspond to 178 MHz in the $2s_{1/2}$ state, 59 MHz in $2p_{1/2}$ state, and 24 MHz in $2p_{3/2}$. Thus, in a low pressure gas containing H_I in 2s or 2p states, Lamb’s conditions are fulfilled (Moret-Bailly [20, 21, 22]), so that a CREIL appears where long paths in excited hydrogen are available.

5.2 Frequency shifts in SNR 1987A.

To leave the Strömgren sphere, the spontaneously emitted Lyman alpha line crosses gas containing some excited hydrogen. In this gas, a CREIL effect transfers energy from the radial beams and to the thermal microwave background. The density of energy of the radial beams is not very large in spite of their high temperature because the small star is seen through a small solid angle. Therefore the radial beams exchange less energy than the thermal background with the sponteously emitted light whose frequency is, consequently, lowered. The emission of light is all the more intense, but less reddened because much of the area of emission is closer to the surface of the sphere. A broad line is obtained, similar to the “Lyman forest”observed in the spectra of the quasars. Michael et al. [23] studied it (fig. 2), supposing an incoherent scattering, but their result was not better than previous

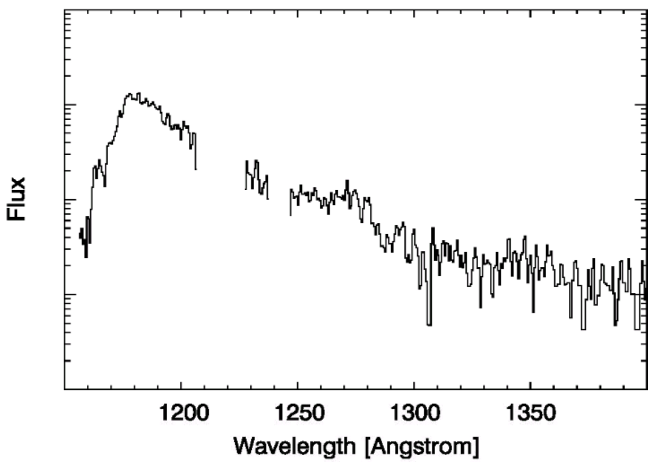

Figure 2: Observed profile from one spatial region. Blank regions are due to contaminants. From Michael et al. [23].

similar studies, for instance by Wolf [24].

The general blueshift of the observed line occurs where light crosses the internal rim of the Strömgren shell: in this thin region where the density of excited hydrogen falls, the density of energy of the tangential rays is large enough to invert the direction of the frequency shift of the low radiance spontaneous emission.

6 Geometry of the rings.

We have assumed that the gas is homogeneous to obtain spherical shells, but the cloud which surrounds the supernova is far from being homogeneous (Sugerman et al. [11]). The Strömgren shell is probably stabilised by regions of higher density. Assume, for instance, that the density is a decreasing function of r, the surfaces of equal density being prolate ellipsoids whose axis is the z' axis of the stars. The far UV ionising light is absorbed by a certain column density of gas, more strongly on the z' axis than in other directions. Thus, the radius of the shell is lower in this direction than in the other, and the shell gets a shape close to an oblate ellipsoid. The cylinder tangent to the ellipsoid, directed to the Earth, is elliptical.

The three rings may be obtained by various shapes of the shell, or by several shells, as in some planetary nebulae. Assuming an axis of symmetry, Martin & Arnett [25] obtained a shape of an hourglass (figure 3 similar to the shapes 4 observed by photon echoes (Sugerman et al. [11]). The rays cC and dD which are not tangent to a

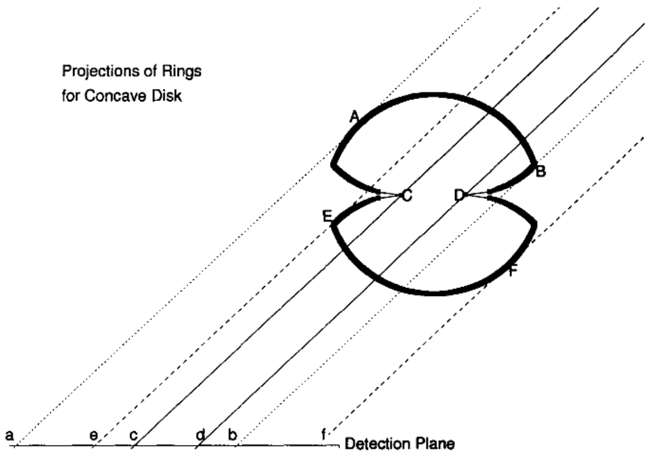

Figure 3: Section of a shell resulting from old explosions of the star, found by Martin & Arnett [25]; the rays cC and dD could be tangent to an inner ellipsoid.

shell in Martin & Arnett figure could be tangent to an added ellipsoid. The hourglass could be illuminated by remaining radial rays and an absorption of a part of the superradiant radiation emitted by the ellipsoid. There are many possible solutions.

7 Conclusion.

Coherent spectroscopy is evidently unable to explain completely the complexity of the optics of the gas surrounding SNR 1987A. But it gives, without any new physics, and with simple hypothesis, a way to understand the disappearance of the star, the spectrum of the disk inside the main ring, how the main ring may remain so bright, the spots, and the spectrum of this ring.

This spectroscopy developed to study laboratory problems applies more widely to SNR 1987A than to other astrophysical objects ("anomalous accelerations" of Pioneer probes, binding of the CMB to the ecliptic, quasar spectra, flattening of the voids between the far galaxies, ...).

A little more attention of astrophysicists to coherent spectroscopy should surely explain a lot of mysterious observations.

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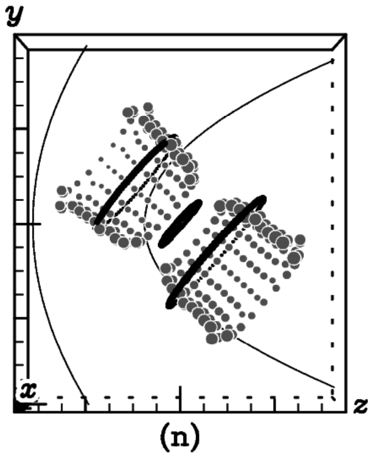

Figure 4: Section of the "circumstellar hourglass"scattering shells found from echoes by Sugerman et al. and the rings (fig. 43n of Sugerman et al. [11]). Compare with fig. 3.

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