The coherent Raman scattering in astrophysics; application to a new model of quasar.

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Abstract

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The "Impulsive Stimulated Raman Scattering" (ISRS), is generally performed using ultrashort laser pulses. It shifts the frequency of the laser beam without any change of the wave surfaces and any appearance of extra lines. ISRS works with the pulses which make the usual incoherent light provided that the interactive medium is a low pressure gas having low frequency Raman transitions, that is an hyperfine spectrum. ISRS has no intensity threshold, but at low intensity level it becomes a linear effect, so that the relative frequency shift $\Delta\nu/\nu$ is nearly constant in the spectrum. This linear effect named "Incoherent Light, Coherent Raman Scattering" (ILCRS) may be confused with a Doppler effect in astrophysics; it explains all optical properties of the quasars, including the debatable ones, in particular the width of the BAL lines, the infrared thermal radiation attributed to hot dust, and the spectral discrepancies attributed to a variation of the hyperfine constant.

1 Introduction

In the spectrum of a quasar, the Ly_α lines and the often associated UV metal lines are generally observed with several redshifts; two families of explanations are proposed: either the absorbing gas is in clouds next to the quasar, or it is in the intergalactic space. In the first case, the redshift is produced by a Doppler effect which requires speeds relative to the kernel of the quasar so high that they seem unreachable [1], in the second case it results from the expansion of the universe, except for the "broad absorption lines (BAL)". As the absorption lines are generally sharp, the active medium must have precisely defined speeds in the first hypothesis, or be

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confined in relatively thin intergalactic clouds in the second hypothesis; an explanation of these confinements is difficult: either they use classical physics, for instance magnetic fields, and they are not fully convincing, or they use unobserved matter. The heating of intergalactic matter requires the proximity of hypothetical sources. These problems may be solved, but it remains debated properties: proximity of a quasar and a galaxy having usually a lower redshift, explanation of a regularity in the distribution of the redshifts.

Already in 1981, hundreds of papers found difficult to explain all redshifts using only the Doppler effect [2]. Thus some physicists looked for an alternative to the Doppler effect, but their proposals did not work, some were so fantastic that the search for this alternative is often considered as not serious. Strangely the coherent Raman scattering was never proposed while Giordmaine et al. [3] had described experiments in which the frequency of ultrashort laser pulses was shifted.

Since, the non-linear light-matter interaction named "Impulsive Stimulated Raman Scattering" (ISRS) has been extensively studied [4, 5, 6, 7]. ISRS shifts the frequencies of the ultrashort laser pulses, introducing no blur, either of the laser beam, or of the spectral line.

Coherent Raman scattering is surely the source of a part of the observed redshift. In this paper, we propose an interpretation of the spectra of the QSOs, using only the usual matter observed by its Lyman and UV spectra and an elementary optical effect deduced from regular spectroscopy.

The sentence "Impulsive Stimulated Raman Scattering"is somewhat ambiguous, it is applied to two different light-matter interactions :

- Literally ISRS shifts the frequency of a single laser beam, the balance of energy being provided by an excitation or de-excitation of the involved molecules; thus its intensity is limited by the saturation of the medium.

- The second one is a combination of two simultaneous preceding effects into a parametric effect; the energy provided by a redshift is exactly compensated by a blueshift, so that the molecules remain in their initial states; as the intensity is not limited, this parametric effect hides generally the simple one, so that the acronym ISRS generally applies to it. Planck's laws attributing a temperature to the beams, the hot beam is redshifted, the cold beam is blueshifted. If the thermal radiation plays the role of cold beams, its blueshift is an amplification, a heating.

In section 2, the previous *ab initio* study of the coherent Raman scattering of incoherent light [8, 9, 10] is avoided, considering that ILCRS is an avatar of the impulsive stimulated Raman scattering. G. L. Lamb [11] gives a general definition of the ultrashort light pulses used to perform ISRS: a light pulse is ultrashort if it is "shorter than all relevant relaxation times". The pulses making the incoherent light may be "ultrashort" if the two relevant relaxation times in the gases are long enough; these relaxation times are the collisional time and the period of the beats of the incident beam with the Raman scattered beam, that is the period of the Raman transition.

Ordinary incoherent light is made of nanosecond pulses whose intensity is much lower than the intensity of laser pulses. The theory of ISRS shows however that ISRS has no intensity threshold: it may work with ordinary light; section 3 shows that while conventional ISRS is nonlinear, so that the frequency shifts depend on the intensity of the laser pulses, at low light level, it becomes linear, so that the relative frequency shift $\Delta\nu/\nu$ is nearly constant in the spectrum; as it is a qualitative change, the new name "Incoherent Light Coherent Raman Scattering" is justified; ILCRS may be confused with a Doppler effect.

Section 4 studies the intensity if ILCRS.

Section 5 shows that ILCRS may hide absorption lines, so that gases such as H_2^+, which are easily destroyed by the collisions and are ILCRS active cannot be observed by their absorption.

Section 6 sets applications if ILCRS which are important to study the quasars.

Section 7 reminds shortly properties of quasars, including debatable ones and section 8 uses the results of section 6 to explain them.

2 ISRS using nanosecond light pulses.

When a light pulse reaches a mono- or poly-atomic molecule, its eigenstates are mixed with other states and the molecule radiates electromagnetic waves; without collisions, quantum or classical computations are the same for all identical molecules on a wave front, so that the phases of the emitted waves are the same, the scattering is coherent, that is the wave surfaces are preserved. During the light pulse, if the frequencies of the incident and scattered lights are different, their relative phase is a linear function of the time. If collisions restart the excitations of the molecules, the phases of scattered light become incoherent: it is the ordinary Raman scattering. If the incident and scattered light have the same frequency, the collisions preserve the relation of phase between the exciting and scattered light, it is the coherent Rayleigh scattering, that is the refraction. The collisions are usually taken into account introducing stochastic phase factors in the off-diagonal elements of the density matrix, not in the diagonal which corresponds to refraction.

To avoid the incoherence with long pulses, that is to have few collisions during long light pulses, low pressures are necessary. Consequently the light-matter interactions are weak, long light paths in the gas are necessary.

The sum of two sine waves of close frequencies is a sine wave modulated at the difference of frequencies; conversely, the modulation of a sine wave allows to split it into components. If the modulated wave is limited near a maximum or a minimum of the envelope, the modulation is negligible so that a single frequency may be detected; a trivial computation shows that the sum of the two waves is a single wave whose frequency is intermediate, in proportion of the amplitudes [9, 10].

While ILCRS may be powerful, a coherent scattering with a larger Raman shift cannot rise well visible lines: the refraction makes the speed of propagation of a discrete Raman line different from the speed of the exciting line; thus, the phases of the fields scattered at a distance "length of coherence" are opposite where the scattered fields meet; these fields cancel [1].

To fulfil this condition with 10 nonoseconds light pulses, the Raman period must be larger than 20 nanoseconds, that is the Raman transition must correspond to radio-frequencies. Such frequencies are common in heavy molecules. In light molecules, these frequencies are found mostly in hyperfine structures whose source is either an odd number of electrons in a polyatomic molecule, or a Stark or Zeeman structure in any mono- or polyatomic molecule.

3 Coherent Raman scattering of ordinary incoherent light (ILCRS) as an avatar of ISRS.

ISRS is a nonlinear scattering: the scattered amplitude is proportional to the square of the incident amplitude, so that the frequency shift is proportional to this amplitude. The computations of ISRS show that, however, it has no intensity threshold. As usual in quantum electrodynamics, the amplitude of an electromagnetic field includes the zero point field: the square of the amplitude of the electric field in ISRS writes $\widehat{E}^2 = (E_0 + E)^2$ where the zero point field E_0 has the same phase than the conventional, usually observed field E. For low light levels, E^2 may be neglected; as the zero point field is nether absorbed or scattered, E_0^2 is not taken into account; the modulus of E_0 being constant in the average, the scattered field which is proportional to $2E_0E$, appears proportional to E, with the instantaneous phase of E_0 and E. Thus the frequency shift does not depend on the intensity of the beam. The scattered field is stimulated by the zero point field, that is it is spontaneous, but coherent in the absence of collisions.

In short, the properties of ILCRS are:

- ILCRS works only in very low pressure gases.

- As the light pulses must be shorter than the period corresponding to the virtual Raman transition, ILCRS works only if the gas has very low energy transitions, that is, generally, if it has an hyperfine structure.

- While in ISRS the frequency shifts depend on the intensity, they do not in ILCRS. An elementary computation shows that the small variation of the relative frequency shift $\Delta\nu/\nu$ in ILCRS results from a dispersion of the spectroscopic constants of the gas.

4 Order of magnitude and dispersion of ILCRS.

ILCRS requires so low pressures, thus so long paths to produce a visible shift that it seems almost impossible to measure it in the labs; an

[1] The beams are supposed wide, forbidding a notable diffraction which, with laser beams, allows a powerful scattering at an angle depending on the ratio of the indices of refraction.

other problem is that among ILCRS active, light molecules, only NO and molecules perturbed by a Zeeman effect are stable. An observation of ISRS with nanosecond pulses involves the same molecular constants than ILCRS; the difference which results from the induction of the scattered light by the zero point field rather than by the a powerful field is easily computed. Thus it seems possible to obtain the ISRS parameters of NO with powerful nanosecond laser pulses and a long cell, then deduce the ILCRS parameters of this gas.

Theoretical computations are difficult because they involve the parameters of lots of Raman transitions of molecules which, even H_2^+, are not well known. Up to now, we have done only a very rough evaluation of orders of magnitude, making, to obtain easily understandable results, the unwarranted hypothesis that the cosmological redshift results from ILCRS in an homogenous intergalactic gas.

Suppose that the active model molecules have only two low-lying levels and one high such that the two Rayleigh and the two Raman probabilities of scattering are the same. A classical computation [8] leads to a needed number of molecules

$$N \approx \frac{16\pi\epsilon_0 mk}{he^2}\left(\frac{F}{f}\right)^2 H_0 T \qquad (1)$$

where m is the mass of the electron, e its charge, F and f the frequencies of the low and high energy transitions, H_0 the Hubble constant and T the temperature of the gas. Choosing $T = 2{,}7\text{K}$ and $F/f = 10^6$, the number of molecules N is 2 per litre. This result is evidently extremely rough, an error of several orders of magnitude is possible.

Suppose that two spectral lines of frequencies ν_1 and ν_2 are shifted by ILCRS in an homogenous gas down to frequencies ν_1' and ν_2', so that $\nu_1' < \nu_2' < \nu_1 < \nu_2$. The conditions of the redshift are exactly the same for both lines between ν_2' and ν_1, so that the measure of ν_1' and ν_2' can only give an information on the dispersion of the redshifts between the intervals (ν_1', ν_2') and (ν_1, ν_2). If the redshifts are much larger than the difference of the eigenfrequencies of the lines, it is difficult to observe the dispersion.

5 Propagation of light in an low absorbing, ILCRS active medium.

The frequencies of a light beam are shifted while the absorption writes lines into the spectrum; an absorption line moves in relation to the spectrum brought by the light; thus the width of the lines is equal to the frequency shift; if the number of lines is large, as in the spectroscopy of vibration-rotation spectra of polyatomic molecules, the lines are mixed, the absorption is almost uniform, the molecules cannot be detected.

If the pressure of the gas is increased, two behaviours may appear :

- if the molecules are slowly or not destroyed by the collisions (NO, OH, NH_2...) ILCRS disappears before a destruction of the molecules, so that the absorption spectrum appears.

- on the contrary, if the molecules are much sensitive to collisions, as H_2^+, they are destroyed before ILCRS disappears. Thus H_2^+ cannot be detected in a nearly stable gas.

While a line is shifted from frequency ν to $\nu - \Delta\nu$, it loses the fraction $\Delta\nu/\nu$ of its initial energy. This energy amplifies the thermal radiation, including the zero point field; generally the zero point field is preponderant, so that the amplified field is isotropic. Thus, if a cloud contains molecules active for the ILCRS, while it redshifts the hot beams without blur, it radiates a thermal field in all directions; if the cloud does not absorb, its behaviour differs from the behaviour of a cloud of dust, because the number of hot photons is not changed; but if the gas absorbs, and if the redshift is large enough to rub the spectral lines, it is very difficult to measure a difference.

Neglecting ILCRS, many dusty clouds are observed; near very bright objects, their existence is debatable because the grains of dust may be repulsed by the pressure of radiation and corroded by the plasma which surrounds them; thus, probably, many apparently dusty clouds are clouds containing only ILCRS active gases.

6 Propagation of light in a plasma and a magnetic field

Suppose that a light beam propagates in a low pressure plasma of atoms, along an axis Ox; in a magnetic field, the atoms have an hyperfine Zeeman structure, so that they shift the frequencies by ILCRS. Suppose that the static magnetic field B has a zero value at point O; near O, with a first order approximation, B is a linear function of x, so that the Zeeman splitting is generally a quadratic function of x. Thus the redshifting power of the gas is proportional to x^2, and to the density of atoms P; if ν_1 is the frequency of a spectral element for $x = 0$, its frequency ν at x may be written :

$$\nu = \nu_1 - \int 3bPx^2 \mathrm{d}x = \nu_1 - bPx^3 \tag{2}$$

where b depends on the gas. Supposing that there are nearly no collisions, the gas has a Doppler lineshape, so that the fraction $\mathrm{d}I$ of the intensity I of the spectral element absorbed at x may be written:

$$\mathrm{d}I = -kPI \exp(-a(\nu - \nu_0)^2)\mathrm{d}x =$$

$$= -kPI \exp(-a(\nu_1 - bPx^3 - \nu_0)^2)\mathrm{d}x \tag{3}$$

In the observed spectra, a single line is seen in different places corresponding to the zeros of the magnetic field, exactly as if sheets of absorbing gas moved with various speeds between a white source and the observer. Figure 1 shows, for various values of b, including $b = 0$, the result of a

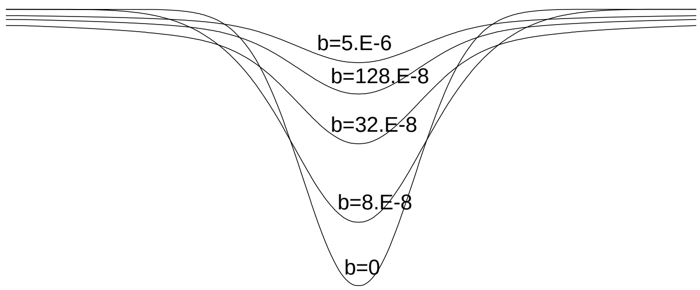

Figure 1: Comparison of a pure Doppler profile (b=0) with the profile resulting from the decrease of ILCRS near a zero of the magnetic field, without saturation (Integration of equation 3 with I constant in the second member).

numerical computation of equation 3 for a low absorption, that is considering I as a constant in the second member; the width of the line at half intensity is not much increased, but this "ILCRS line" has big feet.

Figure 2 shows the result of the computation for large absorptions, such that saturation appears; to allow a comparison simple Doppler- and saturation-widened lines are drawn in the lower part of the figure.

7 Properties of many quasars.

The observations show that, generally:

a) The Lyman absorption spectrum of the quasars is produced by a low pressure gas made of light atoms; the temperature is generally higher than 10 000K.

b) Each Lyman line is observed with several redshifts.

c) Most Lyman lines are sharp.

d) Some quasars have broad absorption lines (BAL); their redshifts are lower than the redshift of the sharper emission lines, larger than the redshift of the sharp absorption lines.

The following properties are debatable:

e) The thermal spectra of the QSOs, hotter for BALQSOs [12], is attributed to hot dust.

f) The density and the temperature of the plasma increase with the redshift [13].

g) The quasars are next to galaxies whose redshifts are lower [14].

h) The values z of the redshifts verify rules such as $\Delta \ln(1+z) = 0.206$ [15, 16]

i) The relative frequency shifts are *nearly* constant in the spectrum [17].

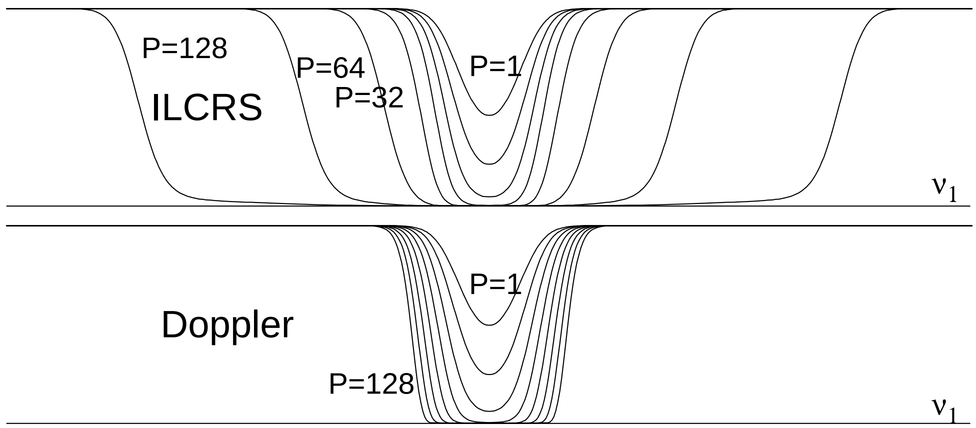

Figure 2: Comparison of the saturation broadening of a pure Doppler profile with the ILCRS profile deduced from a numerical integration of equation 3. Parameters: a=0.003; $b = 8.10^{-8}$; k=0,7; P increases by steps of a factor 2; $\nu_1 - \nu_0$ varies from -500 to $+500$.

8 Simple model of the outer part of a quasar.

Suppose that the quasar is made of a dense, spherical kernel surrounded by a thin atmosphere, origin of the emission lines and by a halo heated by the kernel. The next, sister galaxy (Arp's hypothesis) has not such a halo. The observation of the polarisation, in the microwave domain, shows the existence of a magnetic field.

In a magnetic (or electric field), the Zeeman (or Stark) effect induces a hyperfine structure in the atoms : the plasma around the quasar becomes active for ILCRS. A light beam propagating from the kernel to the earth is mostly redshifted during its propagation in the halo. Section 5 shows that the spectrum seems having absorption lines only in places which correspond to zeros of the magnetic field. Near the kernel, the emission lines are added to the continuous spectrum, they have the maximum redshift. The energy lost by the redshift heats the thermal spectrum, simulating heated dust.

The redshifted frequencies do not depend on the speed of a sheet of gas, or the position of an absorbing cloud, they detect the zeros of a static field. In the lower region of the halo of a BALQSOs, the density of atoms is large enough to broaden the ILCRS lines by a saturation, as shown in figure 2; elsewhere the lines are sharp.

Thus, observations a) to e) are explained; f) is a simple consequence of the decrease of temperature and pressure with the distance to the QSO; as the sister galaxy has no redshifting halo, the explanation of g) is immediate.

Supposing that the variation of the magnetic field obeys a similar rule for all quasars seems reasonable; it would explain h).

The difference of the eigen-frequencies of two lines is known from spectroscopy; the difference of the observed frequencies appears generally true to the difference of frequencies computed with the hypothesis of a constant relative frequency shift $\Delta\nu/\nu$; this usual verification is a strong argument for an interpretation of the redshifts by Doppler or expansion effects; as all optical effects, ILCRS is subject to dispersion; section 4 shows that the consequence of this dispersion is small.

Using good spectrometers and good calibrations of the spectra, Webb et al. [17] found a small variation of $\Delta\nu/\nu$ which they considered as a consequence of a variation of the fine structure constant. It is simpler to suppose that the discrepancy corresponds to the genuine dispersion ILCRS.

9 Conclusion

While optical coherence is taught to all physicists, while we see laser beams almost every day, while ISRS is studied for more than thirty years, it is incomprehensible that Raman coherent effects are ignored in astrophysics. Low pressure clouds, containing ILCRS active molecules such as OH, NH_2, make surely a part of the observed redshifts; a precise evaluation of this part requires hypothesis about invisible galactic and intergalactic gases and spectroscopic measures and computations, but the rough evaluation forbids to ignore ILCRS *a priori*.

With an exception to the origin of radio and microwave frequencies, all properties, sure or debated, of the quasars are explained by the hypothesis of a magnetic field in a plasma next to the quasar, plasma whose properties are found from the Lyman and associated UV spectrum. The theory is much simpler than the conventional theory, it needs only usual matter and regular spectroscopy.

The present hypothesis on the quasars should be refined by a very complicated study of Raman spectroscopy in atoms perturbed by Zeeman or Stark effects, and by a precise study of the magnetic fields near the quasars; but the hypothesis gives so remarkably simple an explanation of all optical observations, with only elementary hypothesis and regular physical concepts, that it has a large probability of being reliable.

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