

IBM Research Report

Stimulated Rayleigh Scattering: A Mechanism for Generating High Ion Velocities in the Solar Winds of Mass-Losing Stars

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Stimulated Rayleigh scattering: a mechanism for generating high ion velocities in the solar winds of mass-losing stars

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A conceptually novel model - one in which stimulated (*i.e.* induced) resonance Rayleigh scattering causes ions of select species to become accelerated to very high terminal velocities in the solar winds of high mass-losing stars - is proposed to explain the general appearance of so-called P Cygni profiles that often dominate the vacuum ultraviolet (VUV) spectra of such stars. In the unit step of the proposed scattering process, a radially outgoing photon (frequency ν_1) that is arbitrarily blueshifted with respect to the rest frame frequency ν_o of the resonance line associated with a P Cygni profile is absorbed from the illuminating star's continuum, a new photon (frequency ν_2) that is very close to ν_o and that propagates in the *backwards* direction (*i.e.* towards the star) is created, and the outwardly directed velocity v of the ion being accelerated is increased by an amount $\Delta v \approx 2h\nu_o / cm_I$, with all three events occurring simultaneously. A monochromatic wave at ν_2 initially forms at some distance from the star, and becomes enormously amplified via the stimulated scattering process as it propagates radially inwards towards the star, all the while retaining a relatively high degree of monochromaticity. The high rate of stimulated scattering enables ions of the resonant species in the solar wind to become accelerated to terminal velocities as high as ~ 1000 km/sec. Since stimulated scattering processes are characterized by pump power thresholds, the model readily explains why only select species are accelerated to very high velocities in a given star's solar wind, and also why a dramatic P Cygni profile for a given ion species can often discontinuously be present or absent when spectra of stars varying only slightly in spectral type are compared.

DOI: ---/PhysRevA. ---

PACS number(s): 42.65.Es, 42.50.Vk, 32.90.+a, 42.65.-k

I. INTRODUCTION

So-called P Cygni profiles of select ion resonances (*e.g.* C IV $\lambda\lambda 1548, 1551$; Si IV $\lambda\lambda 1394, 1403$; NV $\lambda\lambda 1239, 1243$ - see Fig. 1) are often the dominant features in the vacuum ultraviolet (VUV) spectra of O-type [1] and B-type [2] stars, especially giants and supergiants. These features were originally discovered in the late nineteen-sixties by Morton [3] and his colleagues [4] with the use of rocket-based instrumentation, and have since been studied extensively by many astronomers utilizing several orbiting satellites that were successfully launched in the years that followed. Especially productive in obtaining P Cygni spectral data were the fully dedicated *Copernicus* and *International Ultraviolet Explorer (IUE)* satellites, and the *Space Telescope Imaging Spectrometer (STIS)* aboard the *Hubble Space Telescope*.

In a typical P Cygni profile, the star's continuum level in a relatively broad spectral region that is *blueshifted* with respect to a given ion resonance line ν_o is heavily absorbed. (Frequently the ion resonances are doublets, as is the case with the three prominent P Cygni profiles shown in Fig. 1.) The measured frequency displacement from ν_o of the short wavelength limit ν_B of this absorbed region is normally used by astronomers to determine the maximum velocity v_{\max} of the corresponding ions in the

solar wind via the standard relationship $v_B - v_o = v_o v_{\max} / c$. From such Doppler-shift-based analyses of P Cygni profiles, astronomers have inferred that the corresponding ions are strongly accelerated radially away from the stars, reaching in some cases maximum velocities as high as two or three thousand km/sec. For a hot star, the maximum velocity deduced in this manner is frequently greater than the calculated escape velocity $V_e = (2GM/R)^{1/2}$ at the radius R of the photosphere, implying an actual ejection of matter from the star into interstellar space.

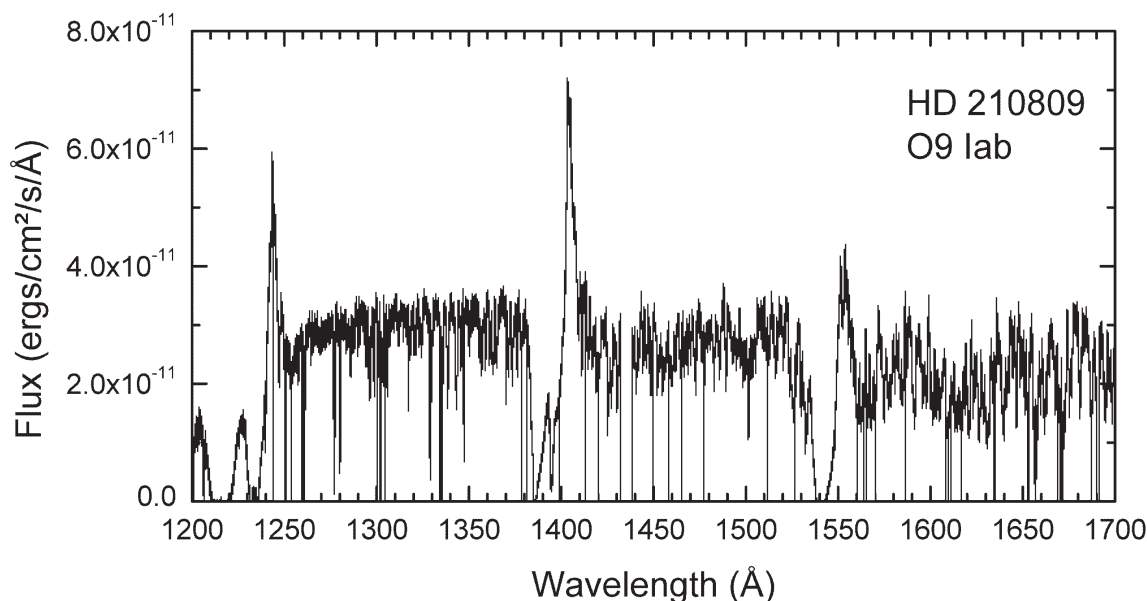


Fig. 1. VUV spectrum of the O9 supergiant HD 210809 recorded with the *Space Telescope Imaging Spectrometer (STIS)* aboard the *Hubble Space Telescope*. (Spectrum downloaded from the *MAST Scrapbook* interactive web site.) The three P Cygni profiles dominating the spectrum are (from left to right) due to N V, Si IV, and C IV ions, respectively. The absorption at 1216 Å is that of H-atom Lyman alpha. A multitude of narrow interstellar absorption lines are present. Wider stellar photospheric absorptions can also be seen.

Reference [5] presents special *Copernicus* VUV spectral scans of the O4 If supergiant ζ Pup, recorded at very high spectral resolution (0.051 Å FWHM), and with an exceptionally high signal-to-noise ratio. For this very hot star, which has $R/R_\odot \approx 20.3$ and $M/M_\odot \approx 100$, it was calculated in [5] that $V_e = 1370 \pm 160$ km/sec. Between 920 Å and 1750 Å, 13 different ion species were found to display P Cygni profiles in ζ Pup, many of them appearing very strong. For example, the ion C III was observed to have a strong P Cygni profile associated with its resonance line at ≈ 977 Å. The blue edge of the heavily absorbed region appeared shifted from 977 Å by ≈ 2710 km/sec, prompting the conclusion that was made in [5] that C III ions in the solar wind of ζ Pup are continually being ejected into space. However, as will be shortly pointed out, according to the nonlinear P Cygni model here being proposed, use of the relationship $v_B - v_o = v_o v_{\max} / c$

to determine the maximum ion velocity v_{\max} attained in a star's solar wind results in an overestimation of this quantity by almost exactly a factor 2.

As noted in [6], current stellar wind theories fall into three broad classes: radiative models, coronal models, and hybrid models. In radiative models, transfer of photon momentum to the gas is assumed to occur through the opacity of the many strong VUV resonance lines that are present. Increased acceleration is believed to result from the progressive Doppler shifting of the line opacity into the unattenuated photospheric radiation field. The stellar wind in existing radiative models is thus assumed to be driven by a purely *linear* effect, commonly known as *radiation pressure*.

In the model here being proposed, a *nonlinear* photomechanism drives the acceleration of the fast moving ions in the solar wind, simultaneously producing the P Cygni spectral profiles one sees in the line-of-sight to the star. Perhaps the most attractive feature of such a nonlinear mechanism would be that it would possess a definite pump power threshold. Only those ion species for which this threshold is reached would be accelerated to very high velocities in a given star's solar wind. Such selectivity is very hard to explain with linear radiative models for solar winds.

In the present paper the focus is placed upon the basic physics of the proposed nonlinear model. No attempt is made to account in detail for fine-grained features appearing in P Cygni profiles of specific stars. The paper is organized as follows. In Sec. II, C II $\lambda\lambda 1334, 1336$ ion resonance spectra recorded in four different stars of roughly the same spectral type are compared to demonstrate the abrupt manner in which P Cygni profiles often appear in star spectra, thus strongly suggesting that a threshold effect of some kind must be involved. In Sec. III, the proposed nonlinear scattering mechanism is outlined. Undoubtedly of some significance is the fact that this mechanism is easily shown to be consistent with the conservation of both energy and momentum. Simple consideration of the manner in which spontaneous resonance Rayleigh scattering (*i.e.* elastic scattering) would occur in the rest frame of an ion being accelerated in a star's solar wind directly leads to identification of the proposed nonlinear scattering mechanism with stimulated (*i.e.* induced) resonance Rayleigh scattering. In the unit step of this stimulated process, three distinct events *simultaneously* occur. (1) An outwardly propagating photon from the star's continuum that is blueshifted with respect to the rest frame frequency ν_o of a strong ion resonance line becomes absorbed by the ion. (2) A photon at exactly ν_o that propagates radially backwards (*i.e.* towards the star) is emitted by the ion, contributing to the intensity of a backward propagating light wave at ν_o that is already present at the position of the ion. (For analytical purposes, this wave is termed the ν_2 wave, but its frequency is $\approx \nu_o$.) (3) The outwardly directed radial velocity v of the ion is increased by $\Delta v \approx 2h\nu_o / cm_1$, *irrespective* of the value of v .

Since, at any point in the solar wind, the transition probability for the unit step to occur is proportional to the product of the outwardly propagating continuum flux and the inwardly propagating light beam intensity I_2 , the likely occurrence of a stimulated scattering regime is therefore here expected, with the ν_2 wave continuously gaining in intensity as it propagates inwardly towards the star. During the entire time it undergoes amplification, the ν_2 wave remains relatively monochromatic, a result of the unit step in the scattering process becoming stimulated by the same wave. However, as the ν_2 wave

propagates inwardly towards the star, the frequency of the pump light that effectively drives the stimulated scattering process continually changes. In this way, continuum light from the star spanning a broad spectral range can contribute to the intensity of the monochromatic ν_2 wave as the latter impinges upon the photosphere of the star.

In Sec. IV, equations that should describe the stimulated scattering process are briefly discussed. However, efforts to provide numerical solutions for these equations have not yet been attempted.

In the concluding section of the present paper (Sec. V), two types of spectroscopic evidence that could help to substantiate the nonlinear model are discussed – fluorescence spectra and two-photon absorption bands. Most P Cygni profiles are observed to possess a prominent fluorescence component. Via simple extension of the stimulated Rayleigh scattering model used to explain P Cygni absorption, one can also comprehend how P Cygni fluorescence is excited. By considering the effect of having the absorption and the fluorescence excitation mechanisms operate in tandem, one can then easily account for the observed fact that the strongest apparent absorption in a P Cygni profile occurs at frequencies considerably blueshifted from ν_o .

In Sec. V it is also suggested that one might seek to identify Doppler broadened absorption bands representing resonantly enhanced two-photon absorption of outwardly propagating continuum light from a star by various ion species present in its photosphere, or just outside. Such two-photon absorption could in principle be induced by the powerful, inwardly propagating, monochromatic beams at the P Cygni ion rest frame frequencies ν_o , provided that near resonances exist between some of the frequencies ν_o and some transitions of the two-photon-absorbing ions. Details of a search for such near resonances in the case of the P Cygni star ζ Pup are described. However, with one possible intriguing exception, this search did not result in the clear identification of any two-photon absorption bands in this star.

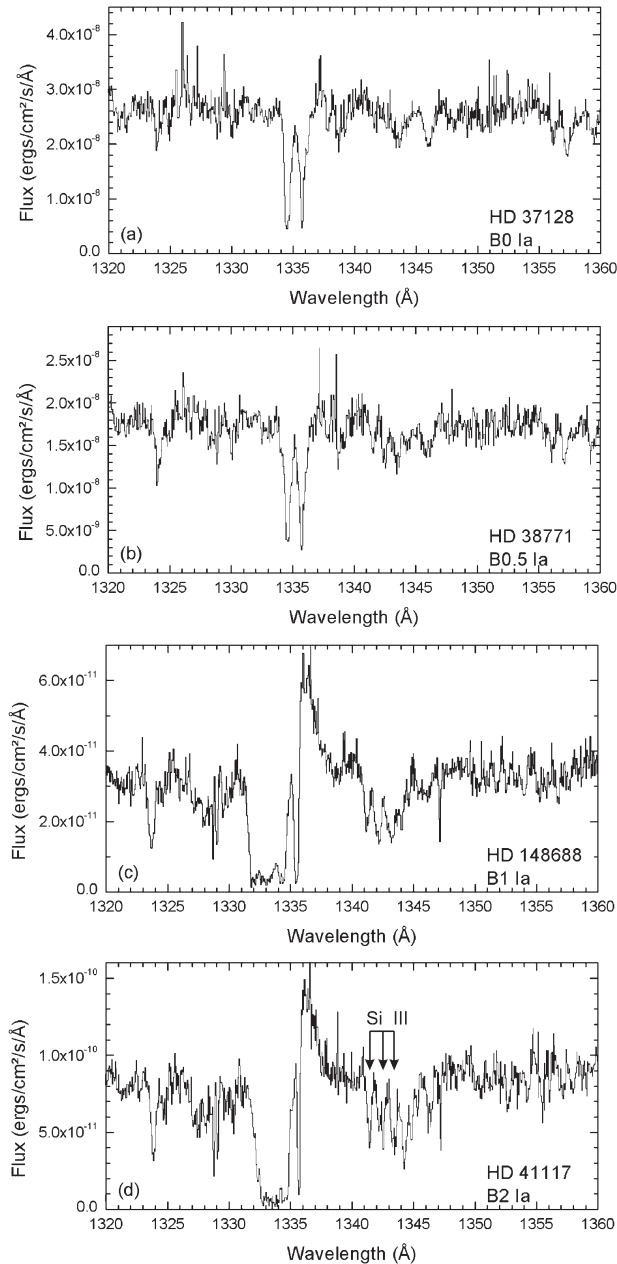
II. P CYGNI PROFILES IN STARS OF ALMOST SIMILAR SPECTRAL TYPES

In Fig. 2, VUV spectra recorded with the *IUE* satellite of four B-type supergiants are displayed over a limited wavelength range that includes the strongly allowed C II ion resonance lines at 1334.5 Å and 1335.7 Å. Each star shown is of a different spectral type, but the difference in temperatures between stars in adjacent spectra is relatively small. In the figure, star temperatures decrease in going from top to bottom.

It is seen that in (a) and (b) the C II doublet appears normally absorbing. Whether the absorbing ions in these two spectra are located in the stars' photospheres, or just outside, is somewhat difficult to judge. It may also be that the lines, at least in part, represent interstellar absorptions. Whatever the case, a significant spectral change is seen to occur in (c), namely, a P Cygni profile, with its characteristic blueshifted region of strong absorption, dramatically appears. From all four spectra, it is clear that this intense new absorption is not simply a broad feature of the stellar photosphere. To explain its sudden appearance via theories based upon the effects of linear radiation pressure also seems excessively difficult. Linear photoexcitation is probably entirely responsible for the comparatively narrow C II absorption lines seen in (a) and (b). These lines are still seen to be present in (c) and (d), and linear absorption may still be the agent that produces them. However, it is quite evident from the spectral sequence shown in Fig. 2 that a

dramatic new mechanism significantly increasing the degree to which continuum light emitted by a star is attenuated can sometimes abruptly become activated. In the present paper it is proposed that this mechanism is stimulated Rayleigh scattering. The rationale for making such a hypothesis is presented throughout the remainder of the paper.

Fig. 2. Montage of VUV spectra of B-type supergiants recorded with the *International*



Ultraviolet Explorer (IUE). (Spectra downloaded from the *MAST Scrapbook* interactive web site.) The spectral region shown here includes the C II $\lambda\lambda$ 1335, 1336 resonance doublet. Stars in adjacent spectra are relatively close in temperature.

III. IDENTIFYING THE PROPOSED P CYGNI MECHANISM WITH STIMULATED RESONANCE RAYLEIGH SCATTERING

In any type of stimulated scattering mechanism, one would expect both momentum and energy to be conserved in the unit step of the process. As already outlined in the Introduction, in the unit step of the process here being invoked to explain P Cygni profiles, three events simultaneously occur at the position of an ion being accelerated in the solar wind. (1) A continuum photon propagating radially outwards from the star, and having an arbitrary frequency ν_1 that is blueshifted with respect to the rest frame frequency ν_o of a resonance transition of the ion, is absorbed by the latter. (2) A photon of frequency ν_2 is emitted by the ion in the direction pointing radially inwards towards the star. (3) The radial velocity of the ion is increased from v to $v + \Delta v$.

Let relativistic corrections initially be neglected. Requiring that energy be conserved in the unit scattering step implies that

$$h\nu_1 \cong h\nu_2 + m_I v(\Delta v), \quad (1)$$

while requiring that momentum be conserved dictates that

$$\frac{h\nu_1}{c} + \frac{h\nu_2}{c} = m_I(\Delta v). \quad (2)$$

From these equations, it then follows that

$$\nu_1 = \nu_2 \frac{\left(1 + \frac{v}{c}\right)}{\left(1 - \frac{v}{c}\right)}. \quad (3)$$

Equation (3) implies that energy and momentum could in principle both be conserved, even if the value of ν_2 were to differ in each scattering event. However, if the photon emitted at ν_2 were always at the same fixed frequency, this would allow the ν_2 light wave to become amplified much more as it propagates radially inwards towards the star, since the rate of stimulated scattering at any point in the solar wind is proportional to the ν_2 light wave intensity at that same point. The latter would obviously be much greater if the backwards-emitted photon in each unit step were always at the same fixed frequency. In the proposed model, not only is this assumed to be the case, but it is also postulated that $\nu_2 \equiv \nu_o$.

One can also attempt to view the unit step in the proposed scattering process simply as spontaneous resonance Rayleigh scattering (*i.e.* elastic scattering) occurring in the rest frame of the ion being accelerated. Viewed in this rest frame, the pumping frequency (*i.e.* the incident continuum photon frequency) is $\nu_1 - \nu_1(v/c)$, since the ion is

receding from the star at velocity v . (Here again, relativistic corrections are being ignored.) Thus, in the ion rest frame, an oscillating dipole moment would be induced at the same frequency, $\nu_1 - \nu_1(v/c)$. This oscillating dipole moment would radiate in all directions. Photons that are emitted in the backwards direction (*i.e.* towards the star) would therefore be at $\nu_2 = [\nu_1 - \nu_1(v/c)] - [\nu_1 - \nu_1(v/c)](v/c)$, implying that

$$\nu_1 = \frac{\nu_2}{[1 - (v/c)]^2}. \quad (4)$$

The values of ν_1 given by Eqs. (3) and (4) are the same to within a factor $[1 - (v^2/c^2)]$, which would result in a difference between these quantities of only about one wavenumber at typical resonance frequencies ($\sim 100,000 \text{ cm}^{-1}$) of solar wind ions moving at $\sim 1000 \text{ km/sec}$. Although the effects of this difference on the proposed P Cygni scattering model would be very small, it is nonetheless of some interest to compare the two scenarios when relativistic effects are taken into account. We here consider first the changes that would occur in the spontaneous Rayleigh scattering picture. Use of the known expression for the relativistic Doppler shift would imply that, in the rest frame of an ion in the solar wind moving away from the star with velocity v , the frequency of an incident continuum photon at ν_1 would be

$$\nu' = \nu_1 \frac{\sqrt{1 - \frac{v^2}{c^2}}}{\left(1 + \frac{v}{c}\right)} = \nu_1 \sqrt{\frac{1 - \frac{v}{c}}{1 + \frac{v}{c}}}. \quad (5)$$

Therefore, the frequency of photons emitted in the direction of the star by a dipole moment oscillating in the ion rest frame at the frequency ν' would be

$$\nu_2 = \nu' \sqrt{\frac{1 - \frac{v}{c}}{1 + \frac{v}{c}}} = \nu_1 \frac{\left(1 - \frac{v}{c}\right)}{\left(1 + \frac{v}{c}\right)}.$$

Interestingly enough, the above equation expresses exactly the same relationship between ν_1 and ν_2 that is represented in Eq. (3). To complete the comparison of scenarios, one should finally consider the equations for conservation of energy and momentum that would hold in the unit step of the proposed scattering process when relativistic effects are included. The equation equivalent to Eq. (1) is:

$$h\nu_1 \cong h\nu_2 + m_I v \left(1 - \frac{v^2}{c^2}\right)^{-3/2} (\Delta v), \quad (6)$$

while that equivalent to Eq. (2) is:

$$\frac{h\nu_1}{c} + \frac{h\nu_2}{c} = m_I \left(1 - \frac{v^2}{c^2}\right)^{-3/2} (\Delta\nu). \quad (7)$$

From Eqs. (6) and (7), an equation identical to Eq. (3) follows. Thus, when relativistic effects are included, the equations relating ν_1 and ν_2 in the unit step of the proposed scattering process and in spontaneous Rayleigh scattering are seen to be identical, strongly implying that the former should be identified with the latter. As has already been emphasized, in the proposed model it is assumed that $\nu_2 \equiv \nu_o$, and that the presence of an intense light wave at this same frequency at the position of every ion in the solar wind *preferentially stimulates* (i.e. induces) the photons produced by the Rayleigh scattering process to be emitted in the backwards direction, while simultaneously causing the ion to be accelerated. *While it is hard to provide the conditions necessary to unambiguously demonstrate stimulated Rayleigh scattering in the laboratory, it is nonetheless quite apparent that the astrophysical environments of hot stars which display P Cygni profiles would offer optimum conditions for this particular type of stimulated scattering to occur.*

In the model, all photons produced by the stimulated Rayleigh scattering process throughout the entire volume occupied by the solar wind occur at the same monochromatic frequency ν_o and propagate radially inwards towards the star. All photons absorbed by the stimulated scattering process are continuum photons that are emitted from the photosphere of the illuminating star and propagate radially away from it. The frequencies of these absorbed photons, which at all points in the solar wind supply the pumping energy needed to drive the stimulated Rayleigh scattering process, span a wide spectral range that originates at ν_o and extends to higher energies. From Eq. (3), an ion moving with radial velocity v will strongly absorb continuum light in a narrow frequency band centered at $\nu_1 = \nu_o \left(1 + \frac{v}{c}\right) \left(1 - \frac{v}{c}\right)^{-1} \approx \nu_o + 2\nu_o(v/c)$. As an ion becomes accelerated more and more, the continuum light it effectively absorbs occurs at higher and higher frequencies. One thus can see how the stimulated Rayleigh scattering process is able to efficiently convert most of the incoherent light continuum photons emitted from a star over a wide, blueshifted spectral range into the same number of essentially monochromatic coherent light photons in the form of a spherical light wave at ν_o that radially converges upon the star's photosphere.

From the above paragraph, one can now comprehend the basis for the statement made in the Introduction that use of the standard relationship $\nu_B - \nu_o = \nu_o v_{\max} / c$ to determine the maximum ion velocity v_{\max} attained in a star's solar wind results in an overestimation of this quantity by almost exactly a factor 2. However, this statement does assume that the most blueshifted absorption occurring in a P Cygni band almost entirely represents *nonlinear* absorption.

From Eq. (7) one has that

$$\Delta v \approx \frac{2h\nu_o}{cm_I}. \quad (8)$$

This equation states that the velocity increase Δv occurring in each unit scattering event is always roughly the same - that is, to a first approximation, Δv is not a function of the velocity v of the ion involved in the scattering event. It depends only on inherent properties of the ion being accelerated in the solar wind. In the case of the C II ion P Cygni profiles shown in the two lower spectra of Fig. 2, one has that $\Delta v \approx 50$ cm/sec. Although each nonlinear scattering event results in only a modest velocity increase for the ion being accelerated, the rate of occurrence of such events will be very large in the region of the solar wind where the particles are being significantly accelerated, due to the Rayleigh scattering process becoming stimulated. In the case of Fig. 2c, the short wavelength limit of the P Cygni absorption region appears offset from the shortest-wavelength C II doublet component by about 200 cm^{-1} . Thus, according to the proposed nonlinear model, v_{max} would here be about 395 km/sec. An ion accelerated to the maximum velocity v_{max} in the solar wind would therefore have had to participate in at least $\sim 790,000$ unit step scatterings.

IV. OUTLINE OF A MODEL FOR STIMULATED RAYLEIGH SCATTERING OCCURRING IN P CYGNI STARS

In principle, one should be able to model the proposed stimulated scattering scenario with a set of differential equations involving a number of dependent and independent variables. Equations for a model possessing minimum mathematical complexity are outlined below, and some discussion is given of the parameters involved. However, at this stage only qualitative statements regarding this model can be made, as attempts have not yet been made to provide computer-based numerical solutions for even this rudimentary system of equations.

In the conceptually simplest type of model, there would be only one independent variable. This would be r , the radial distance from the center of the illuminating star. One primary dependent variable would be $v(r)$, the velocity of an ion in the solar wind at radial position r . Assuming that there is only a single ion velocity associated with each value of r effectively presupposes that the nonlinear ion acceleration process (*i.e.* stimulated Rayleigh scattering) commences at some given radius $R_o > R$ (R being the star's photospheric radius), and that at this radius a spherically uniform, radially expanding flow of ions occurs, with each ion in the flow moving at the same radial velocity $v(R_o)$. Let K_2 represent the total rate at which ions of a given P Cygni species continually cross the surface of the sphere at R_o , *i.e.* $K_2 = 4\pi R_o^2 n_I(R_o) v(R_o)$. Here $n_I(R_o)$ is the value at R_o of another primary dependent variable, the ion density at r , $n_I(r)$. Steady-state conditions are assumed to prevail in the model, and since it is also postulated that *all* of the ions escape into interstellar space, an effective equation of continuity must exist. One therefore would have

$$4\pi r^2 n_I(r) v(r) = K_2. \quad (9)$$

The third primary dependent variable is $\phi_2(r)$, the flux at r of the monochromatic, radially inwardly propagating laser wave at $\nu_2 \equiv \nu_o$. The growth of $\phi_2(r)$ occurs due to stimulated Rayleigh scattering, and can be represented by the equation

$$-\frac{d\phi_2(r)}{dr} = \sigma(r)n_1(r)\phi_1(r)\phi_2(r). \quad (10)$$

With this equation, two additional dependent variables, $\phi_1(r)$ and $\sigma(r)$, appear to have been introduced. However, it is straightforward to write down the functional dependence on r of one of these variables, and the other variable can easily be expressed in terms of the previously introduced dependent variable $\nu(r)$. Both these variables will now be discussed.

The function $\phi_1(r)$ is the star's continuum flux at position r that is effective in pumping the stimulated Rayleigh scattering process occurring at that point. Basically, it represents the continuum light at r contained within a certain fixed narrow band width $\Delta\nu_n$. This band width $\Delta\nu_n$ should approximately correspond to the spectral line width of the inwardly propagating ν_2 laser radiation. Initially, it can be regarded as an adjustable parameter. On the basis of the proposed model, one can write $\phi_1(r) = K_1/r^2$, with K_1 being a constant easily determinable from the emissive properties of the star generating the solar wind. The reason why it is possible to write $\phi_1(r)$ as a simple inverse square function of r follows from the discussion given in Sec. III. At any radius r , the only pump light that is effectively absorbed occurs in a narrow band width $\Delta\nu_n$ that is spectrally located at $\approx \nu_o + 2\nu_o(\nu/c)$. Thus, nowhere in the solar wind is the continuum pump light depleted by ions located at positions with smaller r values.

The function $\sigma(r)$ is an effective two-photon cross-section for the stimulated Rayleigh process. Its functional dependence on r is given by

$$\sigma(r) \approx \frac{\sigma_o}{\left\{ \nu_1(r) \left[1 - \frac{\nu(r)}{c} \right] - \nu_o \right\}^2} \approx \frac{\sigma_o}{\left\{ \left[\nu_o + 2\nu_o \frac{\nu(r)}{c} \right] \left[1 - \frac{\nu(r)}{c} \right] - \nu_o \right\}^2} \approx \frac{\sigma_o c^2}{\nu_o^2 \nu^2(r)}, \quad (11)$$

this equation simply reflecting the fact that excitation is occurring on the wing of a lifetime broadened Lorentzian resonance profile. The constant σ_o can be determined from the radiative properties of the P Cygni resonance transition.

A third independent equation relates two of the three inherently dependent variables to each other. The radial velocity $\nu(r)$ of each ion located in the volume between r and $r + dr$ will be increased by an amount $\sigma(r)\phi_1(r)\phi_2(r)(\Delta\nu)$ per second. Since it takes a time $dr/\nu(r)$ for an ion to reach $r + dr$, one can write

$$v(r) \frac{dv(r)}{dr} = \sigma(r) \phi_1(r) \phi_2(r) (\Delta v). \quad (12)$$

From Eqs. (9), (10), and (12), it appears that obtaining a solution to the system of equations here discussed amounts to solving the following two coupled equations:

$$-\frac{d\phi_2(r)}{dr} = \left[\frac{\sigma_o c^2 K_2 K_1}{4\pi v_o^2} \right] \frac{\phi_2(r)}{r^4 v^3(r)} \quad (13)$$

and

$$v^3(r) \frac{dv(r)}{dr} = \left[\frac{(\Delta v) \sigma_o c^2 K_1}{v_o^2} \right] \frac{\phi_2(r)}{r^2}. \quad (14)$$

All the constants appearing in brackets in these two equations are in principle known for transitions having P Cygni line shapes in stars such as ζ Pup. It would be interesting to see if numerical solutions can indeed reveal a threshold type of behavior, with parameter values in certain ranges resulting in the occurrence of “lasing” in the star’s solar wind.

V. POSSIBLE SPECTROSCOPIC CONSEQUENCES OF THE PROPOSED MODEL

A. The fluorescence component of a P Cygni profile

As has been indicated above, a signature feature of the proposed nonlinear P Cygni model is an intense monochromatic ν_2 laser wave that radially impinges upon the star’s photosphere. Since this wave would be directly unobservable in any line of sight, one should therefore consider what kinds of observable *secondary* effects might result from its presence.

One predictable effect would be *fluorescence* seen in the line-of-sight that is emitted by P Cygni ions moving in the solar wind. As discussed in various texts (*e.g.* [7]), when there is no collision broadening, and the excitation intensity is weak, the Lorentzian cross-section for linear resonant light scattering by a two-level atom exclusively applies to the elastic (*i.e.* Rayleigh) component. The probability of inelastic scattering is zero, *i.e.* no real linear excitation of the atom occurs. The situation becomes entirely different, however, when intense excitation (as produced by a laser beam, for example) is present. Then real excitation of the upper level of the atom can result, even when the exciting light is non resonant (*c.f.* [8]). One thus could expect ions in the solar wind to undergo real transitions to the upper level of the P Cygni resonance, driven by an intense inwardly propagating laser wave at ν_2 . Such ions would then fluoresce. At first glance, it might appear that the fluorescence occurring at $\nu > \nu_o$ would be absorbed in pumping the stimulated Rayleigh scattering processes that occur in the solar wind. However, it can be readily shown that this cannot be the case. Consider an ion in the solar wind moving with velocity v in a direction towards Earth. If this ion becomes inelastically excited by the ν_2

laser wave, the fluorescence it immediately would radiate towards Earth would occur at the frequency $\nu_o + \nu_o(v/c)$. However, it was shown in Sec. III that the continuum pump light necessary to make the same ion undergo stimulated Rayleigh scattering occurs at frequency $\nu_o + 2\nu_o(v/c)$. *Thus, the fluorescence emitted by the ion towards Earth cannot be nonlinearly absorbed anywhere in the solar wind.* (In principle, it could be linearly absorbed to some extent by surrounding ions in the solar wind, but in the proposed nonlinear model this process is being entirely neglected.) Fluorescence in the line-of-sight occurring at $\nu < \nu_o$ will neither be linearly nor nonlinearly absorbed.

In view of the deduction made in the last paragraph, it would appear that, on the basis of the proposed nonlinear model, a rough replica of a typical P Cygni profile could be conceptually constructed in the following manner. Start with the basic continuum level of the star. Subtract from this the blueshifted light that is absorbed in pumping stimulated Rayleigh scattering. To this depleted continuum then simply add the fluorescence intensity radiated towards Earth by all the ions in the solar wind. Such fluorescence will generally be much stronger for $\nu > \nu_o$ than for $\nu < \nu_o$, due to occultation by the star. Via this conceptual construction, a simple explanation is therefore provided for a characteristic observed feature of P Cygni profiles, namely, that the strongest attenuation of the continuum appears to occur at frequencies that are significantly offset from ν_o . In reality, strong attenuation of the continuum may also be occurring much closer to ν_o , but this is masked by the presence of a strong fluorescence signal.

From the fluorescence mechanism here proposed, it also follows that the reddest fluorescent emission observed should have an absolute value frequency offset from ν_o no greater than half that of the bluest P Cygni absorption. In most P Cygni spectra this seems approximately to be the case. However, it is perhaps well to note here that fluorescence appears not to be as intrinsic a feature of P Cygni profiles as is extended blueshifted absorption. For the P Cygni spectra observed in [5], it was noted that the equivalent width of the emission component is always significantly less than that of the absorption component. In the P Cygni profile of N III in ζ Pup, in fact, the fluorescence component is completely absent. It was suggested in [5] that this might be the result of absorption occurring close enough to the stellar surface to hide the emission via occultation by the star. To obtain even a rough estimate of the expected fluorescence profile based upon the nonlinear model would require at least semi-quantitative solutions of equations such as those discussed in Sec. IV to be made. From the present section, it would appear that one should modify those equations by including a loss term for the variable $\phi_2(r)$, in order to represent strong fluorescence being excited.

B. Two-photon absorption bands

In principle, one could seek to directly substantiate the proposed nonlinear model by clearly identifying in a P Cygni spectrum Doppler broadened absorption bands representing resonantly enhanced two-photon absorption of continuum light from the star by various ion species present in its photosphere, or just outside. Such two-photon absorptions could in principle be induced if powerful, monochromatic beams at P Cygni ion rest frame frequencies ν_o were indeed incident upon the star's photosphere, as the

nonlinear model presupposes. For such two-photon absorptions to be strong enough to be detectable, near resonances would have to exist between some of the P Cygni frame frequencies and some of the transitions of the two-photon-absorbing ions.

The authors have attempted to identify such two-photon absorption bands in the case of the P Cygni star ζ Pup. With use of the NIST Atomic Spectra Database web site, spectral intervals extending $\sim 200 \text{ cm}^{-1}$ on either side of the rest frame frequencies ν_o of the strongest P Cygni profiles shown in [5] were examined for likely absorbing-ion candidates, but no convincing ones were found. The spectral intervals examined were as follows: C III ($977 \pm 2 \text{ \AA}$); C IV ($1551 \pm 5 \text{ \AA}$, $1548 \pm 5 \text{ \AA}$); N V ($1243 \pm 3.2 \text{ \AA}$, $1239 \pm 3.2 \text{ \AA}$); Si IV ($1403 \pm 4 \text{ \AA}$, $1394 \pm 4 \text{ \AA}$); N III ($992 \pm 3 \text{ \AA}$, $990 \pm 3 \text{ \AA}$); S VI ($945 \pm 5 \text{ \AA}$, $933 \pm 5 \text{ \AA}$); and O VI ($1032 \pm 5 \text{ \AA}$, $1038 \pm 5 \text{ \AA}$). The most promising coincidence found was between the wavelength (1038 \AA) of one of the O VI doublet components and a strongly allowed C II ion transition originating from a level only 63 cm^{-1} above its ground state (Fig. 3). The difference between the O VI resonance and C II transition frequency is in this case only 55 cm^{-1} . With this scheme (and with another somewhat less resonant one also shown in Fig. 3), one predicts two-photon absorption bands to exist at 1381.7 \AA , 1382.08 \AA , 1382.94 \AA , and 1383.3 \AA , with the latter two being stronger than the former two.

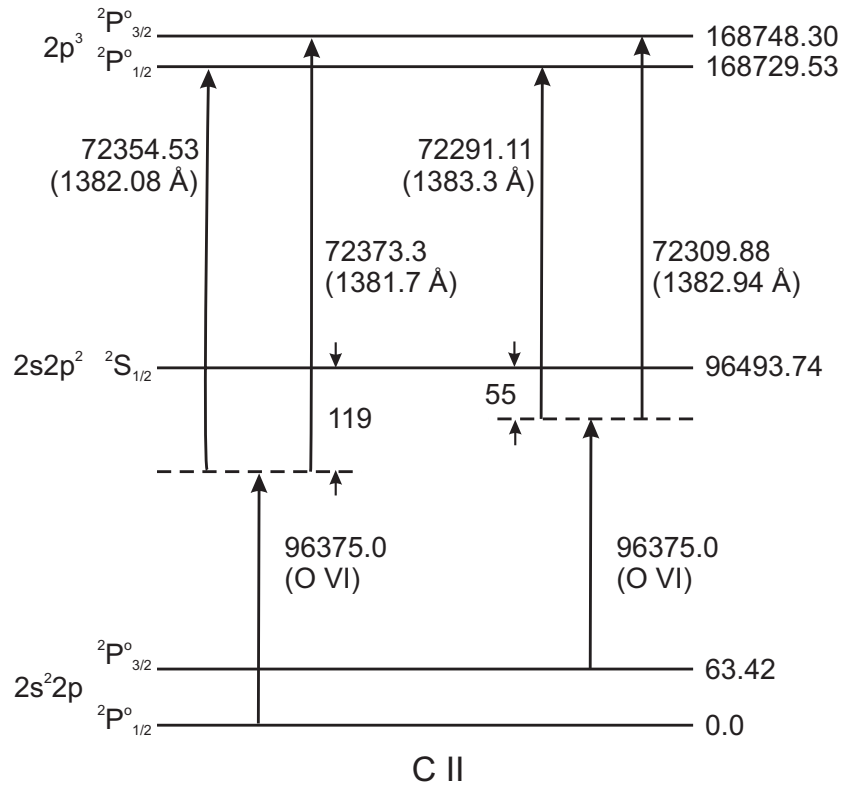


Fig. 3. C II partial energy level diagram showing two-photon absorption transitions that are likely to be induced by application of strong monochromatic coherent radiation at 96375 cm^{-1} , the frequency of the O VI resonance at 1238 \AA .

On the basis of several high resolution VUV *Copernicus* scans of ζ Pup recorded in 1973-1975, interstellar absorption lines seen in the line-of-sight to this star were identified and tabulated by D.C. Morton in [9]. Ref. [9] also contains a table of 52 lines towards ζ Pup that were unidentifiable in 1978. In 1991, Morton published a large compendium [10] of interstellar absorption lines based upon data obtained from many space objects with use of the *Hubble Space Telescope*. Included in this finding list was an updated version of the original unidentified lines list of [9], the number of such lines towards ζ Pup by 1991 having been reduced to 42, largely as a result of the discovery of seven new Fe II lines that were not known in 1978. Still remaining unassigned in 1991 were four lines in ζ Pup occurring as an isolated group at 1382.305 Å (8.9), 1382.593 Å (22.1), 1383.205 Å (30.8), and 1383.720 Å (18.6) (equivalent widths in mÅ in parentheses). In comparing the wavelengths of these four lines with those of the predicted two-photon absorption bands, one should add at least 0.26 Å to each of the latter to account for the fact that the relative velocity of ζ Pup with respect to Earth is -24 km/sec. This assumes that the C II ions are actually located in the photosphere of the star. If the C II ions are located just outside of the star's photosphere, and if additionally they are slowly moving outwards from the latter with radial velocities in the range, say, of 10-20 km/sec, one should add even more to the predicted wavelengths. In any event, one sees that the four unidentified lines in ζ Pup are tantalizingly close to the four predicted two-photon absorption bands. However, despite the existence of these intriguing nearly perfect wavelength matches, it is apparently difficult to argue that C II would not be fully ionized in the photosphere of a star as hot as ζ Pup. Strong C II absorptions are seen in the ζ Pup spectrum, but astronomers believe that these represent interstellar lines.

It is of interest here to comprehend roughly what the maximum intensity of the monochromatic ν_2 wave could be as it impinges upon a star's photosphere. We here consider the case where ν_2 corresponds to the O VI P Cygni resonance at 1032 Å in ζ Pup. In this star, the corresponding blueshifted absorption region extends to about 1020 Å. Under the assumption that roughly 80% of the continuum photons emitted by the star between 1020 Å and 1032 Å are nonlinearly absorbed and entirely converted to photons of the inwardly propagating monochromatic wave at ν_2 , it follows that the intensity of the latter would be roughly 200 kW/cm² as it impinges upon the star's photosphere. In this estimate it is assumed that the temperature of ζ Pup is 50,000K, and that this star emits as a perfect blackbody. It is also here assumed that no loss of ν_2 wave intensity occurs as a result of fluorescence excitation. As outlined in Sec.V A, one actually expects such loss to be quite large.

ACKNOWLEDGEMENTS

P.P.S. is grateful to IBM Research management for having allowed him, as an IBM Fellow Emeritus, the use of office and library facilities for the past two years.

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