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A model for selective line-driven acceleration of ions in the stellar winds of OB-type stars occurring via the nonlinear process of stimulated Rayleigh scattering

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Abstract. 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 stellar winds of OB-type 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 nonlinear scattering mechanism, an ion moving in the stellar wind with radial velocity v becomes accelerated by the nonlinear process when three quantum-mechanical exchanges of energy simultaneously occur. (1) The ion, which is assumed to possess a strongly-allowed optical transition at frequency ν_o, absorbs a photon at $\nu_1 \approx \nu_o + 2\nu_o v/c$ from the illuminating star's continuum. (2) At the same time, the ion also emits a photon at frequency ν_o that propagates radially inwards (*i.e.* towards the star). (3) As a result of (1) and (2), the radial velocity v of the ion becomes increased by an amount $\Delta v \approx 2h\nu_o/cm_I$, thereby allowing overall conservation of both energy and momentum to occur in the unit nonlinear scattering step. A weak monochromatic wave at ν_o initially forms at some distance from the star, and becomes enormously amplified in stimulating the nonlinear scattering process as it propagates radially inwards towards the star, all the while retaining a high degree of monochromaticity. Nonlinear absorption of continuum light, induced by the presence of the intense ν_o wave, both pumps the stimulated scattering process and produces the spectrally-wide blueshifted region of continuum absorption that characterizes a P Cygni profile. Close to the photosphere of a hot star, the presence of the high intensity wave at ν_o can potentially make the stimulated scattering process somewhat more probable than linear scattering. It is here suggested that the high rate of stimulated scattering may enable ions displaying P Cygni profiles to become accelerated rapidly enough to avoid being slowed down via Coulomb coupling with stellar wind protons, thereby allowing such ions to attain terminal velocities as high as a few thousand km/sec. Since stimulated scattering processes processes are characterized by pump power thresholds, the model readily explains why only select species are accelerated to very high velocities in OB-type stellar winds, 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.

Key words. acceleration of particles – radiation mechanisms: non-thermal – stars: winds, outflows

1. 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 (Walborn *et al.* 1985) and B-type (Walborn *et al.* 1995) stars, especially giants and supergiants. These features were originally discovered in the late nineteen-sixties by Morton (Morton 1967) and his colleagues (Morton *et al.* 1969) 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 as-

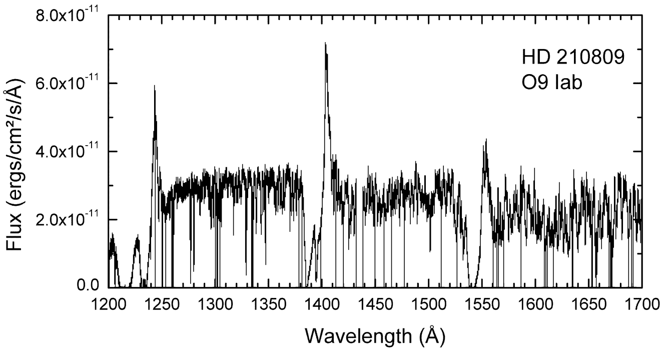

Fig. 1. VUV spectrum of the O9 supergiant HD 210809 recorded with the *Space Telescope Imaging Spectrometer (STIS)* aboard the *Hubble Space Telescope*. (Spectrum downloaded from the *MAST Scrapbook* interactive web site.) The three P Cygni profiles dominating the spectrum are (from left to right) due 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.

tronomers to determine the maximum velocity $v_{\max}$ of the corresponding ions in the stellar wind via the standard relationship $\nu_B - \nu_o = \nu_o v_{\max}/c$. 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, which (more than sufficiently) insures that the accelerated ion species is ejected into interstellar space.

Included in Morton (1976) are 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 Morton (1976) 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 Morton (1976) that C III ions in the stellar 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 $\nu_B - \nu_o = \nu_o v_{\max}/c$ to determine the maximum ion velocity $v_{\max}$ attained in a stellar wind results in an overestimation of this quantity by almost exactly a factor 2.

As noted in Lamers & Cassinelli (1999), current stellar wind theories fall into three broad classes: radiative (*i.e.* line-driven) 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 stellar 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 stellar wind. Such selectivity is very hard to explain with linear radiative models for stellar 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 Sect. 2, 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 Sect. 3, the unit step of the proposed nonlinear scattering process is initially introduced as a simple quantum mechanical event involving two photons and an ion being accelerated in the stellar wind. In this unit step, an ion moving in the stellar wind with radial velocity v becomes accelerated by the nonlinear process when the following exchanges of energy *simultaneously* occur. (1) The ion, which is assumed to possess a strongly allowed optical transition at frequency ν_o, absorbs a photon at $\nu_1 \approx \nu_o + 2\nu_o v/c$ from the illuminating star's continuum. (2) At the same time, the ion emits a photon at ν_o radially backwards (*i.e.* towards the star), adding to the intensity of a spherically symmetrical, radially-backwards-propagating, monochromatic light wave at ν_o that is already present at the position of the ion. (For analytical purposes, this light wave will be termed the ν_2 wave. Its flux (photons cm^{-2} sec^{-1}) will be denoted by ϕ_2.) (3) As a result of (1) and (2), the radial velocity of the ion becomes increased by an amount $\Delta v \approx 2h\nu_o/cm_I$, thereby allowing overall conservation of both energy and momentum to occur in the unit nonlinear scattering step.

Since, for any ion in the stellar wind being accelerated by the nonlinear scattering mechanism, the transition probability for the unit step to occur is proportional to the product of the outwardly propagating continuum flux Ψ_1 (photons cm^{-2} sec^{-1} per c.p.s) and the inwardly propagating light beam flux ϕ_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 Sect. 3, 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 stellar wind directly leads to the identification of the proposed nonlinear scattering mechanism with stimulated (*i.e.* induced) resonance Rayleigh scattering. In the present paper, no distinction is therefore made between the two viewpoints.

In Sect. 4, coupled nonlinear differential equations that should describe the stimulated scattering process are outlined. Although efforts to provide numerical solutions for these equations have not yet been attempted, it is none-the-less indicated how all relevant numerical constants appearing in these equations can be determined.

In the next section of the present paper (Sect. 5), 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 Sect. 5 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.

In Sect. 6 nonlinear and linear P Cygni mechanisms are briefly compared. The effect that Coulomb coupling with protons in the stellar wind should have on ions being accelerated by either of these mechanisms is noted in Sect. 7.

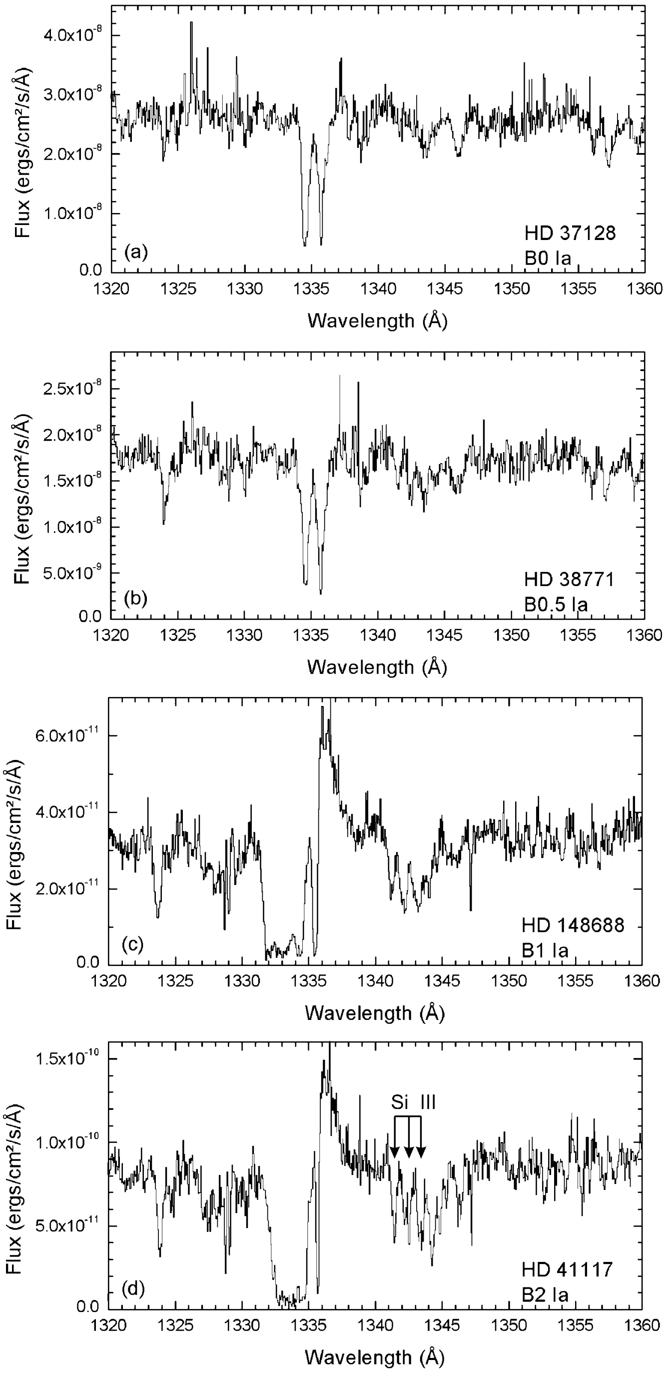

Fig. 2. Montage of VUV spectra of B-type supergiants recorded with the *International Ultraviolet Explorer (IUE).*(Spectra downloaded from the *MAST Scrapbook* interactive web site.) The spectral region shown here includes the C II $\lambda\lambda$1335, 1336 resonance doublet. Stars in adjacent spectra are relatively close in temperature.

2. 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.

3. 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 stellar wind. (1) A continuum photon propagating radially outwards from the star, and having a 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_o 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 $v+\Delta v$. In the Introduction it was stated that $\nu_1 \approx \nu_o + 2\nu_o v/c$, and that $\Delta v \approx 2h\nu_o/cm_I$. We show now that both these equivalences necessarily follow from the requirements that total energy and momentum both be conserved in the unit step, if it is indeed postulated that the frequency of the emitted photon is ν_o.

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

$$h\nu_1 \cong h\nu_o + m_I v(\Delta v), \tag{1}$$

while requiring that momentum be conserved dictates that

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

From these equations, it then follows that

$$\nu_1 = \nu_o \frac{\left(1+\frac{v}{c}\right)}{\left(1-\frac{v}{c}\right)} \approx \nu_o + 2\nu_o v/c, \tag{3}$$

while Eq. (2) is equivalent to

$$\Delta v \approx 2h\nu_o/cm_I. \tag{4}$$

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 “ν_o” $= [\nu_1 - \nu_1(v/c)] - [\nu_1 - \nu_1(v/c)]\,(v/c)$, implying that

$$\nu_1 = \frac{\text{“}\nu_o\text{”}}{[1-(v/c)]^2}. \tag{5}$$

The values of ν_1 given by Eqs. (3) and (5) are the same to within a factor $\left[1-(v^2/c^2)\right]$, which would result in a difference between these quantities of only about one wavenumber at typical resonance frequencies ($\sim$ 100,000 cm^{-1}) of stellar wind ions moving at $\sim$ 1000 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 stellar wind moving away from the star with velocity v, the frequency of an incident continuum photon at ν_1 would be

$$\nu' = \nu_1 \frac{\sqrt{1-\frac{v^2}{c^2}}}{\left(1+\frac{v}{c}\right)} = \nu_1 \sqrt{\frac{1-\frac{v}{c}}{1+\frac{v}{c}}}. \tag{6}$$

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

$$\text{“}\nu_o\text{”} = \nu' \sqrt{\frac{1-\frac{v}{c}}{1+\frac{v}{c}}} = \nu_1 \frac{\left(1-\frac{v}{c}\right)}{\left(1+\frac{v}{c}\right)}. \tag{7}$$

Interestingly enough, the above equation expresses exactly the same relationship between ν_1 and ν_o (or “ν_o”) 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:

$$h\nu_1 \cong h\nu_o + m_I v \left(1-\frac{v^2}{c^2}\right)^{-3/2} (\Delta v), \tag{8}$$

while that equivalent to Eq. (2) is:

$$\frac{h\nu_1}{c} + \frac{h\nu_o}{c} = m_I \left(1-\frac{v^2}{c^2}\right)^{-3/2} (\Delta v). \tag{9}$$

From Eqs. (8) and (9), an equation identical to Eq. (3) follows. Thus, when relativistic effects are included, the equations relating ν_1 and ν_o (or “ν_o”) 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 the presence of an intense radially-inwards-directed light wave at ν_o at the position of every ion in the stellar wind *preferentially stimulates* (*i.e.* induces) photons produced in the Rayleigh scattering process to be emitted in the backwards direction, while simultaneously causing the ion to be accelerated radially outwards. By contrast, in spontaneous Rayleigh scattering, the emitted photons are radiated in all directions equally. The presence of a strong light wave at ν_o in effect selectively stimulates a specific Rayleigh scattering process to occur with very high probability. Were the ν_o wave not present at all, spontaneous Rayleigh scattering could still theoretically occur when primary radiation is applied at $\nu_1 \approx \nu_o + 2\nu_o v/c$, but it would be very much weaker than spontaneous Rayleigh scattering occurring when the primary radiation is applied at $\nu_1 \approx \nu_o + \nu_o v/c$, due to the latter process being exactly resonant. In both these cases the emitted radiation would occur in all directions. In the former case, the radiation emitted in the backwards direction would be at ν_o. In the latter case, the light radiated in the backwards direction would be at $\nu_o - \nu_o v/c$.

While it is hard to demonstrate unambiguously stimulated Rayleigh scattering in the laboratory, it is nonetheless quite apparent that the astrophysical environments of hot stars which display P Cygni profiles could realistically provide optimum conditions potentially allowing 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 stellar wind occur at the same monochromatic frequency ν_o and propagate radially inwards towards the star. All photons nonlinearly 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 stellar 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 nonlinearly absorb continuum light in a narrow frequency band centered at $\nu_1 = \nu_o \left(1 + \frac{v}{c}\right)\left(1 - \frac{v}{c}\right)^{-1} \simeq \nu_o + 2\nu_o(v/c)$. 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 radial velocity $v_{\max}$ attained in a stellar 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. (4) one has that $\Delta v \approx 2h\nu_o/cm_I$. 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 stellar 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 stellar 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 stellar wind would therefore have had to participate in at least $\sim$ 790,000 unit step scatterings.

4. 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 are possible, 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 stellar 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 $v(R_o)$. For simplicity, we here take $R_o \equiv R$. Let K_R represent the total rate at which ions of a given P Cygni species continually leave the star's photospheric surface to subsequently become accelerated in its stellar wind, *i.e.*$K_R = 4\pi R^2 n_I(R)v(R)$. Here $n_I(R)$ is the value at R 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 being accelerated escape into interstellar space (*i.e.* the effect of the star's gravitational field is entirely being neglected in the present treatment), an effective equation of continuity must exist. One therefore would have

$$4\pi r^2 n_I(r)v(r) = K_R. \tag{10}$$

The third primary dependent variable is $\phi_2(r)$, the flux (photons cm^{-2} sec^{-1}) at r of the monochromatic, radially-inwards-propagating, spherically symmetric 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

$$-\frac{d\phi_2(r)}{dr} = \sigma_{nl}(r)n_I(r)\Psi_1(r)\phi_2(r). \qquad (11)$$

With this equation, two additional dependent variables, $\Psi_1(r)$ and $\sigma_{nl}(r)$, appear to have been introduced. However, $\Psi_1(r)$ is the stellar continuum flux per unit frequency width (photons cm^{-2} sec^{-1} per c.p.s. ≡ photons cm^{-2}) in the spectral vicinity of ν_o, and $\sigma_{nl}(r)$ is a nonlinear scattering cross-section which will be shown below to vary with r as $1/v^2(r)$. From Eq. (11), the units of $\sigma_{nl}(r)$ are seen to be cm^4.

One can justify the use of Eq. (11) as an equation which can describe stimulated Rayleigh scattering on the basis of the Kramers-Heisenberg dispersion theory, references to which may be found in Jones & Stoicheff (1964), a pioneering paper in which induced absorption at optical frequencies was first reported. In the latter work, the induced absorption occurred via Raman transitions, the discovered effect eventually becoming termed *Inverse Raman Absorption (IRA)* or *Inverse Raman Scattering (IRS)*. In IRA (IRS), one applies both a very intense, monochromatic, laser beam having a frequency ν_o and an intense continuum to a sample of ground-state molecules possessing an allowed Raman transition at frequency ν_M. Under this excitation, the molecules are stimulated to emit radiation at ν_o and, at the same time, to absorb radiation at $\nu_o + \nu_M$ from the continuum. A Raman spectrum can therefore be recorded via absorption bands appearing in the continuum spectrum after the latter has passed through the molecular sample.

The stimulated Rayleigh scattering mechanism proposed in the present paper is directly analogous to the mechanism that operates in the case of IRA (IRS). An ion in the stellar wind being accelerated at position r is simultaneously irradiated both by an intense monochromatic laser field at ν_o and by the broadband continuum light emitted from the star. Induced absorption of continuum radiation by such an ion occurs at $\nu_1 \approx \nu_o + 2\nu_o v(r)/c$. Thus, $2\nu_o v(r)/c$ is a frequency directly analogous to the Raman frequency ν_M in IRA (IRS).

In Jones & Stoicheff (1964) the following formula is given for the rate at which molecules in the lower state are stimulated to simultaneously emit radiation at ν_o and to absorb radiation at $\nu_o + \nu_M$. The total transition probability $(t.p.)_{tot}$ for this process is given by

$$(t.p.)_{tot} = \frac{16\pi^4}{h^4}\int |\mu|^2\rho(\nu_o + \nu_M)\left[\rho(\nu_o) + \frac{8\pi h\nu_o^3}{c^3}\right]d\nu_o. \qquad (12)$$

Here μ is a matrix element for two-photon processes which will be evaluated below; $\rho(\nu_o + \nu_M)$ and $\rho(\nu_o)$ are the *energy densities per unit frequency width* of the two incident light beams. The dominant term involving $\rho(\nu_o + \nu_M)\cdot\rho(\nu_o)$ gives the probability for the simultaneous occurrence of stimulated emission at ν_o and stimulated absorption at $\nu_o + \nu_M$, while the term involving $\rho(\nu_o+\nu_M)\cdot(8\pi h\nu_o^3/c^3)$ represents the very small spontaneous Raman scattering transition probability.

Modifying Eq. (12) to apply to the case of stimulated Rayleigh scattering is reasonably straightforward. Recalling that the ρ's in Eq. (12) are all energy densities *per unit frequency width*, one immediately sees that one should be able to write down an expression for the probability per unit time that an ion in the stellar wind at position r will undergo a unit nonlinear scattering event:

$$(t.p.)_{stim} = \left(\frac{16\pi^4\nu_o^2\,|\mu(r)|^2}{h^2c^2}\right)\phi_2(r)\Psi_1(r). \qquad (13)$$

If one defines $\sigma_{nl}(r)$ to be the function in parentheses in the above equation, then Eq. (11) immediately follows. The dependency of $\sigma_{nl}(r)$ upon r will now be determined.

By considering only the spontaneous Rayleigh scattering term in the equation analogous to Eq. (12), one can obtain the functional dependence of $|\mu(r)|^2$ upon r as follows. Assume for the moment that $\phi_2(r) = 0$ but that a narrow-band continuum light beam spectrally centered at $\nu_1 \approx \nu_o + 2\nu_o v(r)/c$ is present at the position of an ion moving with radial velocity $v(r)$ in the stellar wind. From the analog to Eq. (12), one would deduce the spontaneous Rayleigh scattering transition probability for this ion to be:

$$(t.p.)_{spont} = \left(\frac{128\pi^5\nu_o^4\,|\mu(r)|^2}{h^2c^4}\right)\phi_1(r), \qquad (14)$$

where $\phi_1(r)$is the total flux (photons cm^{-2} sec^{-1}) of the narrow-band continuum beam. Since the left-hand side of Eq. (14) is related to the cross-section $\sigma_{sp}(r)$ for spontaneous Rayleigh scattering via

$$(t.p.)_{spont} = \sigma_{sp}(r)\phi_1(r), \qquad (15)$$

one has:

$$\sigma_{sp}(r) = \frac{128\pi^5\nu_o^4\,|\mu(r)|^2}{h^2c^4}. \qquad (16)$$

The expression for the differential cross-section $d\sigma_{sp}/d\Omega$ for spontaneous resonant Rayleigh scattering is well known. For a two-level atom (ion), with damping neglected, it takes the form:

$$\frac{d\sigma_{sp}(r)}{d\Omega} \approx \frac{e^4\omega_o^4x_{1g}^4}{\hbar^2c^4\,|\omega_1(r) - \omega_o|^2}, \qquad (17)$$

where x_{1g} is the transition moment for the two-level atom (ion).

Multiplying the expression for $d\sigma_{sp}/d\Omega$ in Eq. (17) by 4π to get $\sigma_{sp}(r)$, one then finds from Eqs. (16) and (17) that

$$|\mu(r)|^2 = \frac{e^4x_{1g}^4}{2\,|\nu_1(r) - \nu_o|^2}. \qquad (18)$$

In Eq. (18), the frequency offset $\nu_1(r) - \nu_o$ is the one viewed *in the rest frame of the moving ion, i.e.* $\nu_1(r) - \nu_o \approx \nu_o v/c$. One finally finds the nonlinear scattering cross-section $\sigma_{nl}(r)$ to be:

$$\sigma_{nl}(r) = \frac{8\pi^4e^4x_{1g}^4}{h^2\,[v^2(r)]} = \frac{8\pi^4\mu_{1g}^2}{h^2\,[v^2(r)]}, \qquad (19)$$

where μ_{1g} is the transition *dipole* moment. One easily verifies the units of $\sigma_{nl}(r)$ to be cm^4.

The continuum photon flux per unit frequency width, $\Psi_1(r)$, appearing in Eq. (11) can simply be written as $\Psi_1(r) = \Psi_{1R}\cdot(R^2/r^2)$, where Ψ_{1R} is the value of this quantity at the star's photospheric surface at frequencies near ν_o. The reason why it is here possible to write $\Psi_1(r)$as a simple inverse square function of r follows from the discussion given in Sect. 3. The only pump light that is effectively absorbed by ions at radius r that are being accelerated by the nonlinear mechanism occurs in a narrow-width spectral interval located at $\approx \nu_o + 2\nu_o v(r)/c$. Thus, nowhere in the stellar wind is the continuum pump light depleted by ions located at positions with smaller r values.

A third independent equation relates two of the three inherently dependent variables [*i.e.* $v(r)$, $\phi_2(r)$, and $n_I(r)$] to each other. The radial velocity $v(r)$ of each ion located in the volume between r and $r + dr$ will be increased by an amount $\sigma_{nl}(r)\Psi_1(r)\phi_2(r)(\Delta\nu)$ per second. Since it takes a time $dr/v(r)$ for an ion to reach $r + dr$, one can write:

$$v(r)\frac{dv(r)}{dr} = \sigma_{nl}(r)\Psi_1(r)\phi_2(r)(\Delta\nu). \tag{20}$$

From Eqs. (4), (10), (11), (19), and (20), it appears that obtaining a solution to the system of equations here discussed amounts to solving the following two coupled differential equations:

$$-\frac{d\phi_2(r)}{dr} = \left[\frac{2\pi^3 e^4 x_{1g}^4 K_R \Psi_{1R} R^2}{h^2}\right]\frac{\phi_2(r)}{r^4 v^3(r)} \tag{21}$$

and

$$v^3(r)\frac{dv(r)}{dr} = \left[\frac{16\pi^4 \nu_o e^4 x_{1g}^4 \Psi_{1R} R^2}{hcm_I}\right]\frac{\phi_2(r)}{r^2}. \tag{22}$$

All the quantities appearing in brackets in these two equations are either fundamental physical constants or parameters that easily can be specified for transitions having P Cygni line shapes in stars such as ζ Pup. In seeking to obtain numerical solutions to these equations, one might have to specify the presence of a very small "background" or "noise" signal which can "seed" the growth of the ν_2 wave. In theory, such "seed" light could be provided via spontaneous Rayleigh scattering. Consider that there must be some value of r ($r = r_T$) beyond which the stimulated Rayleigh scattering process effectively ceases. At this radius, the ions will have attained their maximum radial velocity, *i.e.* $v(r_T) = v_\infty$. At this same radius, all continuum light from the star spectrally lying between ν_o and $\nu_o + 2\nu_o v(r_T)/c$ will (ideally) have been depleted in pumping stimulated Rayleigh scattering processes occurring over the entire range $r_T > r > R$. However, for all values $r > r_T$, at frequencies $\nu_1 \geq \nu_o + 2\nu_o v(r_T)/c$, the continuum light will be undepleted. This undepleted continuum light in theory could still be weakly scattered via *spontaneous* Rayleigh scattering. Undepleted continuum light at $\nu_1 \approx \nu_o + 2\nu_o v(r_T)/c$ would be scattered the most, since it is the most resonant. Ions no longer being accelerated in the stellar wind would re-radiate this light in all directions. In the backwards direction (*i.e.* towards the star), the re-radiated light would be peaked at ν_o, effectively providing "seed" light for amplification by stimulated Rayleigh scattering occurring at $r < r_T$. 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 dramatic occurrence of "lasing" in the stellar wind. In Sect. 6 , a numerical estimate of the rate of nonlinear scattering near the photospheric surface will be made.

5. Possible spectroscopic consequences of the proposed model

5.1. 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 to a P Cygni-type star emitted by ions being accelerated in the stellar wind. As discussed in various texts (*e.g.* Loudon 2000), 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.* Knight & Milonni 1980). One thus could expect ions in the stellar wind to undergo real transitions to the upper level of the P Cygni resonance, driven by an intense inwardly propagating laser wave at ν_o. 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 stellar wind. However, it can be readily shown that this cannot be the case. Consider an ion in the stellar 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 stellar wind.* (In principle, it could be linearly absorbed to some extent by surrounding ions in the stellar 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 stellar 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 Morton (1976), 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 Morton (1976) 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 Sect. 4 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.

5.2. Two-photon absorption bands

In principle, one could seek to directly substantiate the proposed nonlinear model by clearly identifying in the spectrum of an OB-type star containing P Cygni profiles 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 rest 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 ~ 200 cm^{-1} on either side of the rest frame frequencies ν_o of the strongest P Cygni profiles shown in Morton (1976) were examined for likely absorbing-ion candidates, but no convincing ones were found. The spectral intervals examined were as follows: C III (977 ± 2Å); C IV (1551 ± 5Å, 1548 ± 5Å); N V (1243 ± 3.2Å, 1239 ± 3.2Å); Si IV (1403 ± 4Å, 1394 ± 4Å); N III (992 ± 3Å, 990 ± 3Å); S VI (945 ± 5Å, 933 ± 5Å); and O VI (1032 ± 5Å, 1038 ± 5Å). The most promising coincidence found was between the wavelength (1038 Å) 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}.

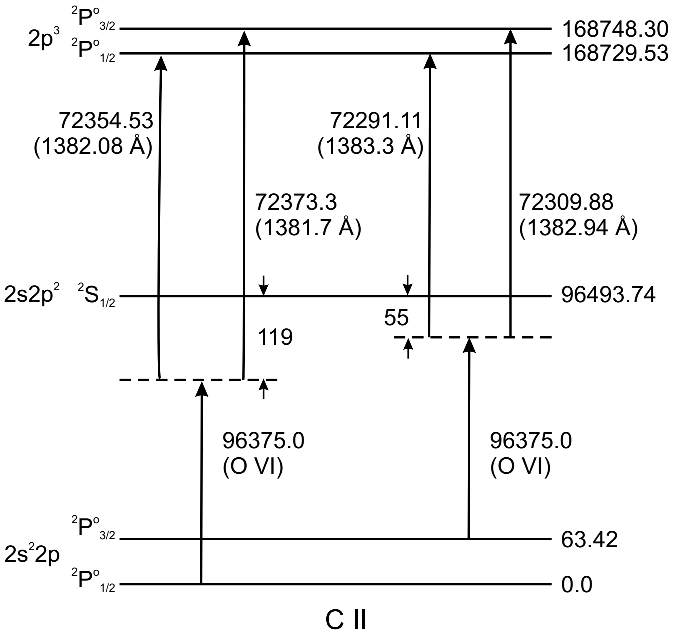

Fig. 3. C II partial energy level diagram showing two-photon absorption transitions that are likely to be induced by application of strong monochromatic coherent radiation at 96375 cm^{-1}, the frequency of the O VI resonance at 1038 Å.

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 Å, 1382.08 Å, 1382.94 Å, and 1383.3 Å, with the latter two being stronger than the former two.

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 in Morton (1978). This same publication also contains a table of 52 lines towards ζ Pup that were unidentifiable in 1978. In 1991, Morton published a large compendium (Morton 1991) 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 Morton (1978), 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). 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 intriguingly close wavelength matches, it would be 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/cm^2 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 Sect. 5.1, one actually expects such loss to be quite large.

6. Linear vs. nonlinear P Cygni mechanisms in luminous stars

Current theoretical models for line driven winds of luminous hot stars are all based upon the effects of *linear* resonant absorption of continuum light emitted by such stars. In such models, the essential physical processes that occur are in many ways similar to those that characterize the nonlinear model described in Sect. 3. For example, it is easy to demonstrate that the outwardly directed momentum transfer to an atom or ion in the stellar wind in a linear scattering event is $h\nu_o/c$ – *i.e. half* the value occurring in the unit step of the nonlinear process. In the linear theory, just as in the nonlinear case, the Doppler shifts of atoms or ions moving in the outer portions of a stellar wind in principle allow the atoms to absorb undiminished continuum photons in their line transitions. However, the light that effectively drives the acceleration of an atom moving with a given radial velocity v in the case of the nonlinear mechanism is blueshifted from ν_o *twice* as much as in the linear case. This implies that occurrence of the former mechanism (*i.e.* stimulated Rayleigh scattering) would have already strongly depleted the supply of continuum photons necessary to drive the linear process everywhere in the stellar wind. Since the stimulated Rayleigh scattering process should occur at its highest rate very close to the photosphere of the illuminating star, it is even possible that in very bright stars it completely prevents linear scattering from being an effective acceleration mechanism.

To obtain a general understanding of the various ways in which the dependent variables $\phi_2(r)$, $v(r)$, and $n_I(r)$ potentially can vary with r in the nonlinear scattering model would require having the capability to provide numerical solutions to the coupled differential equations of Sect. 4. However, a few attributes of this model can simply be determined without the use of computers. One of these is the probability per unit time that an ion which is being accelerated in the stellar wind undergoes a unit nonlinear scattering step. Combining Eqs. (13) and (19) to obtain this probability, one finds it to be

$$(t.p.)_{stim} = \left(\frac{8\pi^4 e^4 x_{1g}^4}{h^2\left[v^2(r)\right]}\right)\phi_2(r)\Psi_1(r). \qquad (23)$$

This transition probability will be a maximum close to the photospheric surface of the hot star. Let us specifically consider the case of a C III ion in the initial stages of being accelerated in the stellar wind of ζ Pup via stimulated Rayleigh scattering occurring on the strong two-level transition at 977Å. Although the actual oscillator strength of this transition is $f \approx 0.8$, we will here take it to be 1. For a two-level transition at 1000Å having $f = 1$ and a J=0 ground state, the product $e^2 x_{1g}^2$ is approximately 2.13 x 10^{-35} cm^{2}esu^2 ($x_{1g} \approx 1$ x 10^{-8} cm). Assuming ζ Pup to emit a continuum corresponding to a blackbody temperature at 50,000K, one finds that, at ≈ 1000 Å, $\Psi_1(R) \approx 0.35$ x 10^{10} photons cm^{-2}. Let us assume that the monochromatic ν_2 wave has an intensity of 200 kW cm^{-2} (the value roughly estimated at the end of Sect. 5) as it impinges upon the photosphere of ζ Pup. Thus, $\phi_2(R) \approx 10^{23}$ photons cm^{-2} sec^{-1} .

The transition probability in Eq. (23) depends very strongly on the radial velocity of the ion being accelerated. For $v(R) \approx 1$ km sec^{-1}, and with all other parameters chosen as in the previous paragraph, one calculates the transition probability to be ≈ 2.8 x 10^8 sec^{-1}. Interestingly enough, this is about 3 times faster than the transition probabilty for linear line-driven scattering. The latter is given by

$$(t.p.)_{lin} \approx \left(\frac{\pi e^2 f}{m_e c}\right)\Psi_1(R), \qquad (24)$$

and for the same parameters used in calculating the nonlinear scattering probability, has the value ≈ 0.92 x 10^8 sec^{-1}.

7. Effect of Coulomb coupling on linear and nonlinear acceleration mechanisms in luminous stars

In current theories of line-driven stellar winds in OB-type stars, the following situation is widely believed to prevail (Lamers & Cassinelli 1999). It is postulated that radiative acceleration of the *entire* stellar wind is provided by ions of abundant elements such as C, N, and O, which can absorb and re-emit vacuum ultraviolet (VUV) photons in a few strong resonance lines that occur in this region of the electromagnetic spectrum. However, such ions constitute only about 10^{-5} of the total ion population of the stellar wind, the latter essentially being a hot plasma largely composed of protons, He^{2+} ions, and electrons. The main stellar wind components are thus optically non-absorbing, and cannot therefore be radiatively driven. However, it is generally believed that, through a mechanism known as C*oulomb coupling*, the momentum gained by the continually occurring absorption and re-emission of continuum photons in the resonance lines of the relatively few active ion species becomes efficiently transferred to the entire stellar wind, resulting in *all* components of the latter eventually becoming accelerated to velocities as high as a few thousand km sec^{-1}. Thus, the current picture of an OB star wind is that it represents a steady, one-component outflow of matter leaving the star with a final velocity that can be as great as a few hundredths of the speed of light.

The principal astronomical *spectral* evidence for inferring that very high velocities can be present in the winds of bright OB-type stars is the existence of the spectrally-wide, blueshifted regions of absorption that characterize P Cygni profiles. These are clearly present in both the spectrum of Fig. 1

and in the two lower spectra of Fig. 2. However, looking at the two upper spectra of the latter figure, one immediately wonders why these do not contain similar evidence pointing to the existence of high velocities. Even more puzzling is the fact that, although there is only a small difference in star temperatures corresponding to the second and the third spectra in Fig. 2, spectral evidence of high terminal velocities is only present in the latter spectrum.

Various astronomers have from time-to-time questioned the validity of the one-component OB-star wind model. In particular, stellar wind models for which the Coulomb coupling is insufficient to distribute the momentum gained via repeated absorption and emission events involving an active ion species over all the components of an outgoing stellar plasma have been calculated by Springmann & Pauldrach (1993) and by Babel (1995). In both these papers, the authors did indeed conclude that the assumption of Coulomb coupling might not be valid in the case of line-driven stellar winds of late-B-type and A-type main sequence stars - because the stellar winds in these stars are relatively light - but that Coulomb coupling should almost certainly be satisfied in earlier-B-type and in all O-type stars. Since understanding the reasoning that underlies such conclusions may be helpful in resolving, for example, the apparent paradoxes noted above in Fig. 2, we now briefly highlight the essential aspects of these classical arguments.

Transfer of momentum from the absorbing ions to the field particles (*i.e.* the protons, He^{2+} ions, and electrons in a stellar wind) becomes efficient if the time t_S for slowing down these ions via Coulomb interactions with the field particles is small compared to the time t_D required for the radiatively driven ions to gain a large drift velocity with respect to the field particles. Estimates of t_S are usually made on the basis of the theory presented in Ch. 5 of Spitzer (1962). We now summarize those aspects of this theory which become most relevant when radiatively-driven ions are accelerated in a stellar wind.

Equation (5-28) of Spitzer (1962) is a general expression for the slowing-down time t_S that has two important limiting cases. If w represents the mean velocity of the the radiatively-driven ions at some point in a stellar wind, and if w much exceeds the root mean square velocity of the field particles, then the expression for t_S becomes:

$$t_S \approx \frac{w^3 m_I^2}{4\pi e^4 (1 + m_I/m_H) n_e Z_I^2 \ln\left[\frac{3}{2 Z_I e^3}\left(\frac{k^3 T_e^3}{\pi n_e}\right)^{1/2}\right]}, \tag{25}$$

where, in the above equation, it is for simplicity assumed that the field particles are only protons and electrons.

In the limiting case represented by Eq. (25), one sees that t_S varies as w^3, implying that Coulomb coupling with the stellar wind plasma can no longer slow down line-driven ions in the stellar wind that are moving sufficiently rapidly. These ions can thus move freely in the wind without any attenuation occurring of their radial velocities. There is also the other extreme limit, *i.e.* when w is much less than the random velocity of the field particles. For this case the expression for t_S becomes:

$$t_S \approx 11.7 \frac{A^2 T_e^{3/2}}{(A+1) n_e Z_I^2 \ln\left[\frac{3}{2 Z_I e^3}\left(\frac{k^3 T_e^3}{\pi n_e}\right)^{1/2}\right]}. \tag{26}$$

When Eq. (26) is applicable, the mean velocity of the ions in the stellar wind will approach zero exponentially, with a time constant t_S. There is no velocity dependence in the expression for t_S in this equation.

Since one is here interested to compare the time t_D for an active species ion emerging from the photospheric surface of a star to be accelerated to a radial velocity comparable to the drift velocity of the field particles in the stellar wind with the appropriate Coulomb coupling slow-down time t_S, it is apparent that one should use Eq. (26) in estimating the latter.

We begin by evaluating Eq. (26) for a star temperature T = 50,000K. From Lamers & Cassinelli (1999), one finds that it is reasonable to assume that an OB stellar wind has a plasma temperature $T_e \approx 0.5T$, and that the field particle density n_f ($\equiv n_e$) would typically be in the range $10^8 \leq n_e \leq 10^{12}$. For the hot star here assumed, we (somewhat arbitrarily) take n_e to be 10^{11} cm^{-3}. Evaluating Eq. (26) for the case of C III ions (A=12), one finds $t_S \approx 114\mu$sec. (Evaluating t_S with use of Eq. (8.7) in Lamers & Cassinelli (1999) gives $t_S \approx 72$ μsec for the same choice of parameter values.)

The most probable thermal velocity for protons contained in a plasma at $T_e \approx$ 25,000K is $\approx$ 2.0 x 10^6 cm sec^{-1}. For stellar wind ions driven via linear absorption and re-emission of continuum light, the acceleration is given by

$$g_I = \left(\frac{h\nu_o}{c m_I}\right)(t.p.)_{lin}, \tag{27}$$

with $(t.p.)_{lin}$ being the expression in Eq. (24). A value $(t.p.)_{lin} \approx$ 0.92 x 10^8 sec^{-1} was calculated for the present choice of parameters at the end of Sect. 6. Therefore, in the present case $t_D \approx$ 654 μsec, *i.e.* $t_D \gg t_S$, implying that conditions for Coulomb coupling should be well satisfied. Thus, one would expect that the momentum gained by the line-driven C III ions would be continually redistributed among the protons of the stellar wind plasma. There would be no chance for the ions being accelerated to exhibit a “run away” effect in the wind, attaining very high radial velocities largely because they have become decoupled from the protons in the stellar plasma.

Let us now explore whether Coulomb coupling would likewise hold if the C III ions were accelerated by the stimulated Rayleigh scattering mechanism proposed in the present paper. In this case, one would evaluate the acceleration of C III ions located at the photosphere of the star by multiplying the value of $(t.p.)_{stim}$ given in Eq. (23) by $\Delta\nu \approx 2h\nu_o/cm_I$. For the same astronomical parameters that have thus far been assumed in Sects. 6 and 7, one finds $t_D \approx 107$ μsec , a value roughly six times shorter than the time required for the ions to attain a radial velocity equal to the thermal velocity of the field particles when the former are accelerated by the linear mechanism. For the parameter choices here made, one sees that with the nonlinear mechanism, t_D is predicted to be at least roughly equal to t_S.

As a result of the various above rough estimates, and to explain the apparent paradoxes we feel are present in Fig. 2, the authors would like to propose a new - simple, but striking - hypothesis regarding *OB-type* stellar winds. This is that whenever an ion species displays a definite P Cygni profile in a stellar wind (*e.g*. Fig. 2[c]), those ions are largely being accelerated via the stimulated Rayleigh scattering mechanism, *and* are initially accelerated fast enough by this mechanism to be able to overcome the effects of Coulomb coupling. Such ions are in effect "run away" ions, with the momentum they gain via stimulated Rayleigh scattering largely not being redistributed among the field particles in the stellar wind. On the other hand, if the stimulated Rayleigh scattering process is *not* occurring in a given stellar wind (*e.g*. Fig. 2[b], ions of an active species will still become accelerated via the usual linear line-driven mechanism. However, these ions will not initially be accelerated fast enough to overcome the effects of Coulomb coupling, and since the momentum they gain must therefore continually be transferred to the field particles, the former will never achieve very high terminal velocities – certainly not on the order of $c/100$. Some broadening of the ion resonance lines might become apparent, reflecting the fact that in the long run such ions most likely do acquire some momentum, even though they continually undergo multiple (absorption-emission-momentum transfer) cycles as they move away from the illuminating star. However, it is hard to imagine how the motion of such ions could lead to any P Cygni profiles being produced.

The hypothesis proposed above has directly evolved from considerations about whether or not Coulomb coupling holds in an OB-type stellar wind. When the accelerating mechanism is the linear one, the answer seems fairly clear that it indeed does, and this certainly appears to be the current view of most astronomers. In the linear case, moreover, no apparent way of even conceptually increasing the strength of the ion acceleration mechanism exists. The acceleration is simply that given by Eq. (27).

On the other hand, in the case of the nonlinear accelerating mechanism, the maximum initial ion acceleration possible remains somewhat nebulous. To obtain the relatively large nonlinear transition probability and acceleration rates in the present section and in Sect. 6, we assumed the relatively low *radial* velocity value $v(R) \approx 1$ km sec^{-1}. However, the most probable thermal velocity for a C III ion located just adjacent to a star's photospheric surface in a 25,000K plasma would be ≈ 5.9 km sec^{-1}, and a serious reader might therefore question whether our choice of the parameter value for $v(R)$ was realistic. Our response to such a question would be as follows. Although C III ions moving at ≈ 5.9 km sec^{-1} *normal* to the photospheric surface would indeed be accelerated much less than what we had calculated, they will nonetheless still be accelerated to some extent, since all ions with $v(R) \geq 0$ can theoretically be resonantly excited by the nonlinear mechanism. However, of more importance here, all C III ions moving at ≈ 5.9 km sec^{-1} in the same plasma, but having *radial* velocities $v(R) \leq 1$ km sec^{-1} will be accelerated by the same mechanism *much more strongly* than we had calculated. One can even speculate that a form of velocity redistribution of the active ions in the plasma at $r \approx R$ might here be occurring. In this scenario, ions in the thermal plasma that move predominantly tangentially to the photospheric surface instantly undergo rapid radial acceleration and are injected into the stellar wind, while ions in the same plasma that move with predominantly radial velocities are more likely to be *kinetically scattered* into tangential directions, in effect replacing those ions which were injected into the stellar wind by stimulated Rayleigh scattering. A complete theory should take into account all such aspects of the problem.

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