RC23641 (99831) June 23, 2005
Astrophysics/Astronomy

IBM Research Report

H_2 DIBs Model Revisited

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H_2 DIBs Model Revisited

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ABSTRACT

A theory advanced by the authors several years ago that H_2 molecules located in photon dominated regions (PDRs) surrounding bright stars are the carriers of the diffuse interstellar absorption bands (DIBs) is reexamined in the light of a recently proposed hypothesis that line-driven acceleration of select species ions in the stellar winds of OB-type stars can occur via the nonlinear process of stimulated Rayleigh scattering. In the model describing the latter process, radially-outwards-directed acceleration of an ion species possessing a resonance transition at ν_o occurs simultaneously with generation of intense, relatively monochromatic, radially-inwards-propagating, coherent light at this same frequency, with continuum light from the star over a wide spectral range (*blueshifted* with respect to ν_o) providing the necessary pump power to drive the stimulated scattering process. To explain how DIBs could originate, this model is now modified as follows. Replacing the stellar wind ions of the original model are H_2 molecules and H atoms located in a PDR close to an illuminating star. Both neutral species become nonlinearly accelerated radially outwards from the star via stimulated Rayleigh scattering, and concomitant generation of intense, radially-inwards-propagating, monochromatic coherent light occurs at Ly-α and at select H_2 transition frequencies. However, unlike what happens to ions in a strong OB-type stellar wind, the accelerations received by both the H_2 molecules and H atoms are not sufficient to allow their escape from the star's gravitational field, and they eventually fall back to the base of the PDR. As the neutral species particles approach the latter, they become *decelerated* by the same stimulated Rayleigh scattering processes that accelerated them radially outwards - this time, however, with *redshifted* continuum light from the star being absorbed. Again, intense monochromatic laser light aimed at the star at Ly-α and at select H_2 frequencies is concomitantly produced. This dynamic process continually repeats itself. With a rational basis thus provided for postulating the presence within a PDR of intense, monochromatic, coherent VUV radiation at Ly-α and at specified H_2 frequencies, it becomes much simpler both to identify and to justify those nonlinear photonic mechanisms which should lead to selective absorption occurring at DIB frequencies on transitions between H_2 excited states. Furthermore, on the basis of the dynamic PDR model here postulated, one can (via the Doppler effect) plausibly account for the random juxtaposition of broad and narrow DIBs that occurs throughout the entire DIB spectrum. In essence, this arises because H_2 molecules in levels with different rotational quantum numbers become nonlinearly accelerated/decelerated by different amounts.

Subject headings: line: identification – line: formation – radiation mechanisms: non-thermal

1. Introduction

In May of 1994, the first major conference focusing entirely on the baffling problem of identifying the carriers of the diffuse interstellar bands (DIBs) was held at the University of Colorado, in Boulder. From even a perfunctory reading of the subsequently published book (Tielens & Snow 1995) containing the invited papers presented at the meeting, one would gather that there was a growing sentiment among the conference participants that the DIB carriers would soon be shown to be large, complex molecules. More than ten years have now passed since the Boulder conference was held. Despite intensified, technically sophisticated efforts (*e.g.* Araki *et al.* 2004; Thorburn *et al.* 2003; McCall *et al.* 2002; Snow, Zukowski, & Massey 2002; Walker *et al.* 2001; Sarre 2000; Ball, McCarthy, & Thaddeus 2000; Krelowski *et al.* 1999; Tulej *et al.* 1998, and many others) to identify such molecules made during this period by several world class teams of astronomers, chemical kineticists, and spectroscopists, the situation remains today exactly as it was in 1994 – *i.e.* not a single band in the total DIB spectrum (now known to contain more than 250 bands) has been convincingly assigned to an optical transition of any molecule, atom, or ion! Considering that the spectra of the strongest DIBs were already carefully recorded and precisely characterized by astronomers (*e.g.* Herbig 1975) at least 30 years ago, and that conventional optical absorption spectroscopy is a fully developed field of science that has been extensively employed to probe atomic and molecular structure for a very long time, it is now perhaps reasonable to begin to suspect that the up-to-the-present total lack of success in identifying the carrier(s) of the DIB spectrum is the result of assuming that the bands in this spectrum are produced via the effect of *linear absorption.*

As far back as 1934 (*c.f.* Merrill 1936), astronomers have been able to demonstrate vividly and conclusively that the DIBs do not originate in the *photospheres* of the stars that provide the background light for their viewing. (Figure 1 constitutes a convincing modern-day proof of this statement.) Thus, technically speaking, the DIB carriers are known to be located in interstellar space. Most astronomers that have made serious efforts over the years to identify the DIB carriers have further interpreted this to mean a location *deep* in interstellar space, *i.e.* far from any intense light-emitting space objects, such as the very stars that provide the background light for viewing the DIBs. If it were possible to demonstrate irrefutably that the DIB carriers are indeed located in deep interstellar space, then, of course, linear absorption would be the only photonic mechanism that could give rise to the DIBs.

At about the same time as the Boulder DIBs conference, the present authors began to propose an entirely different explanation for the DIBs. They suggested that the DIBs could possibly represent absorptions induced to occur by some means on transitions between *excited state* levels of H_2, notwithstanding the fact that such levels lie $\sim$100,000 cm^{-1} above the ground state, and would therefore be unpopulated unless the H_2 molecules happened to be located near an object that strongly emitted vacuum-ultraviolet (VUV) light, or unless the molecules were embedded in a plasma in which electron impact excitation occurred. In their first serious attempt to account for some of the DIBs with an H_2 model (Sorokin & Glownia 1995, – hereafter referred to as paper I), the authors attempted to show that the wavelengths of all (twelve) DIBs appearing in the interval 768-788 nm in a comprehensive DIB catalog that had just been published (Jenniskens & Désert 1994) were consistent with the pattern of absorptions that should result from allowed transitions connecting the four lowest rotational levels of the $C9(^1\Pi_u^+)$ state of H_2 with rotational levels of an unknown $^1\Sigma_g^+$ state postulated to exist at higher energy. To enable even the simplest type of spectroscopic analysis to be performed, it had to be assumed that the rotational energies of the postulated H_2 singlet *gerade* state were determined by a formula involving a single rotational constant B, *viz.* $E(J) = BJ(J+1)$. However, far more unrealistic were the basic photonic excitation mechanisms postulated in paper I. Noting that the H_2 transitions $C9-11RJ'', J''=1-4$ are all approximately resonant ($\Delta = 5-25$ cm^{-1}) with the frequency (82259 cm^{-1}) of Ly-α radiation, the authors proposed that the former could be strongly driven by incoherent Ly-α radiation generated via H^+- electron recombination in an ideal Strömgren sphere plasma enveloping a very hot (O5) star, totally ignoring the well known fact that DIBs are widely seen in lines-of-sight to much cooler stars. However, even with such a bright illuminating star,

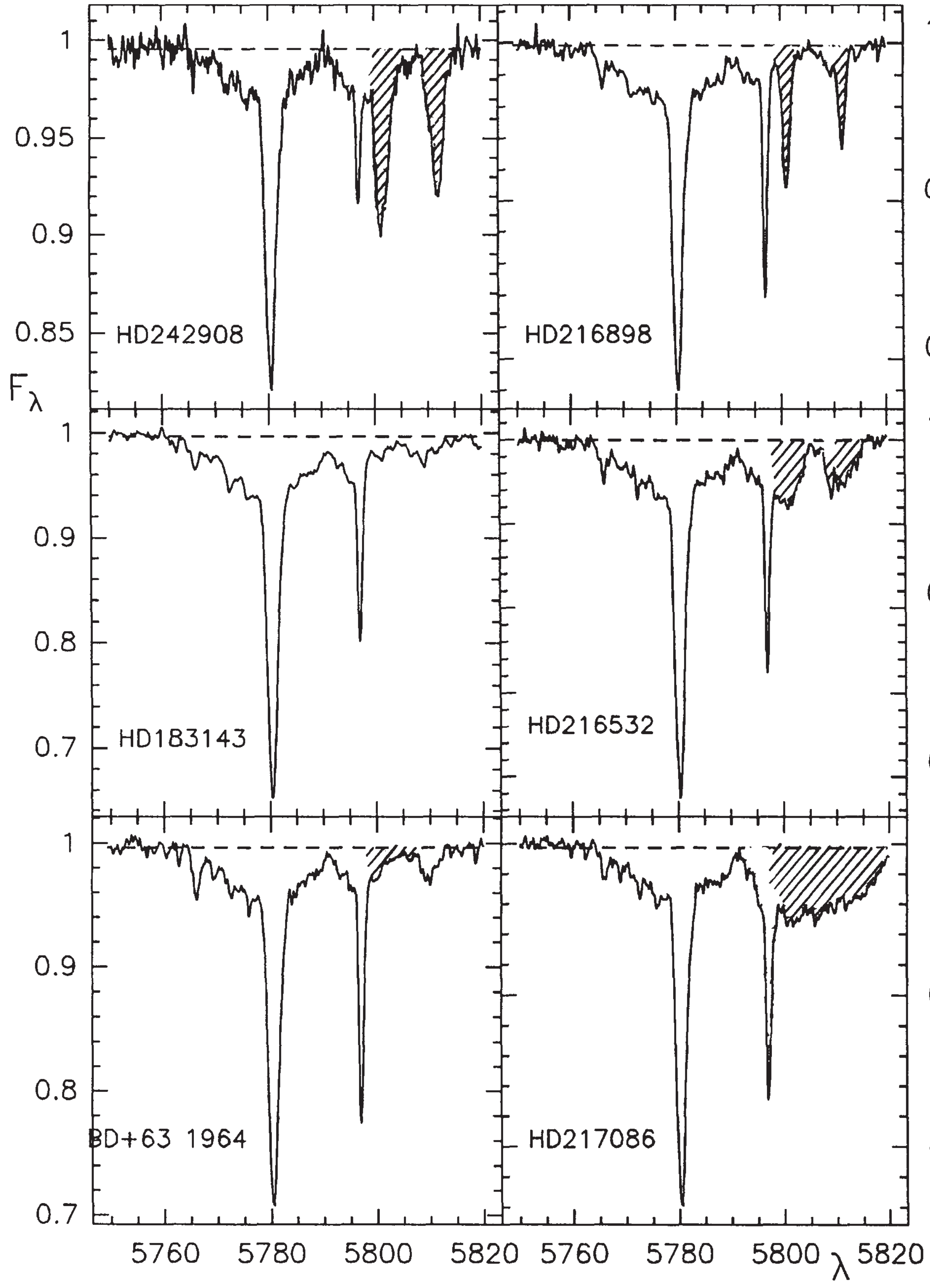

Fig. 1.— Individual spectra of reddened B (left) and O (right) stars with differing stellar rotational velocities. Stellar lines are hatched. Figure taken from Jenniskens & Désert (1993), with permission.

the maximum intensity of the escaping Ly-α radiation at the Strömgren radius R_S would in theory only be $\sim$200 μW cm^{-2}, with such intensity being distributed over a spectral width $\sim$50 cm^{-1}. (The presence of ubiquitous cosmic dust within the Strömgren sphere would make even this small intensity much less.) In retrospect, the authors should have realized that such radiation would be far too weak to excite significantly any H_2 molecules which might be present in the $X11, J'' = 1 - 4$ levels. In addition, no consideration was given in I to the fact that the rates of X →B, C absorption processes that would occur in the vicinity of R_S would be far too low to populate extensively (via sequential absorption and fluorescence) the $X11, J'' = 1 - 4$ levels, despite the fact that these levels are metastable.

By 1995 interest in the problem of identifying the DIB carriers had already become fairly widespread in scientific circles. Thus, it was not surprising that, immediately following the publication of I, a laser physics group at the Vrije Universiteit in Holland successfully performed a convincing laboratory experiment (Hinnen & Ubachs 1995) that was able to check decisively the specific DIB assignments that were proposed in I. In Hinnen & Ubachs (1995), the H_2 quantum levels $C9(\Pi_u^+)$, $J' = 1-3$ were directly populated by a tunable VUV laser at $\sim$86 nm. These levels were then used as absorber states for a second excitation step accomplished with use of a tunable near-IR laser. Via transitions to autoionizing doubly excited states of H_2, many resonances with greatly varying widths were observed. However, the frequencies and linewidths of these resonances were not consistent with those of the DIBs in the range 768-788 nm, nor with the predictions made in I.

The results reported in Hinnen & Ubachs (1995) were sufficiently convincing to make the present authors discard their early H_2 DIBs model. Additional impetus for them to do this came from the astronomy community in the form of a published critical comment by T.P. Snow (Snow 1995), who accurately detailed the serious spectroscopic inconsistencies and unsurmountable astrophysical problems that were present in the H_2 DIBs model of I. However, the possibility that the DIBs might originate from nonlinear photoexcitation of H_2 continued to intrigue the present authors, and they soon published a new paper (Sorokin & Glownia 1996b, hereafter referred to as paper II), in which DIBs were again assigned to excited state transitions of H_2. In paper II, more than 70 DIBs were assigned to strongly allowed H_2 transitions originating from various B- and C-state levels and terminating on higher known singlet *gerade* levels. In making the DIB assignments of II, the authors were at least careful to ascertain that the frequency of an H_2 transition to which a DIB was assigned did indeed fall within the error limits listed in Jenniskens & Désert (1994) for the measured DIB frequency.

However, in hindsight it becomes apparent that most of the nonlinear H_2 photoexcitation mechanisms invoked in II were conceptually wrong. Throughout II, it was hypothesized that, via the combined effects of elastic scattering and diffusion, a significant build up of starlight photon density could occur in the H_2-containing cloud in the spectral vicinities of strong H_2 resonance lines to B- or C-state levels originating from either X0, J''=0 or X0, J''=1. In both the Abstract and main text of II, it was suggested that this enhanced photon density might be sufficient to pump broadband stimulated Raman scattering (SRS) processes in which generation of broadband Stokes-wave light occurs on P(2) and P(3) transitions leading back to X0. However, in the *Note added in manuscript* included in II, the authors specifically backed away from the suggestion that such Stokes-wave generation could occur, essentially because there appeared to exist no mechanism to rapidly relax H_2 molecules driven to the SRS terminal levels X0, J''=2 and X0, J''=3 back to the levels X0, J''=0 and X0, J''=1 from which the SRS processes originated. It was finally concluded in II that the DIBs must therefore simply result from simultaneous two-photon absorption processes, with radiatively trapped light about Cn-0R0, Cn-0R1, Cn-0Q1, Bn-0R0, Bn-0R1, and Bn-0P1 transitions providing the photons for the first step.

The main conceptual difficulty with II centers on the assumption that *significant* photon density enhancement would occur via the combined effects of elastic scattering and diffusion. This would be true only if, during each elastic scattering step, the frequencies of the incident and radiated photons were always exactly the same. However, as long recognized by physicists and astronomers, some form of *frequency redistribution* always occurs during elastic scattering, even at vanishingly small densities of the atomic or molecular scatterers. Extensive calculations existing in the literature demonstrate that only very modest photon density enhancements would occur in astrophysical environments. Thus one would expect the effectiveness of the main photoexcitation mechanism invoked in II to be exceedingly small.

Of the 70 H_2 transitions assigned to DIBs in II, only *two* correspond to R and P transitions occurring from a specific singlet *ungerade* level (B7, J'=4) to rotational levels belonging to the same singlet *gerade* state (EF 24, $J = 5$ and EF 24, $J = 3$). Although this strongly pointed to the existence of a very selective photoexcitation mechanism, no basis for such selectivity was provided by the final mechanism for producing DIBs adopted in II, *i.e.* two-photon absorption. An even more serious deficiency in the model of II was that no convincing mechanism was suggested to account for the observed pervasive occurrence of *spectrally broad bands* in the canonical DIB spectrum.

Publication of II was followed by another critical review of our work by T.P. Snow (Snow 1996), who emphasized in particular that it would be very difficult for astronomers to believe that an interstellar VUV field could be intense enough to allow the proposed two-photon absorption process to occur. This is essentially the same criticism as the main one discussed above.

Somewhat prior to the publication of II, additional (VUV/visible) double-resonance experiments (Hinnen & Ubachs 1996) were conducted by the Vrije Universiteit group to check revised DIB assignments (Sorokin & Glownia 1996a) that the present authors had attempted to make after having corrected a number of spectroscopic mistakes that were present in I. This still involved a model with C9 rotational levels serving as resonant intermediate states, but the focus was shifted to the spectral range 7000-7400Å. In Hinnen & Ubachs (1996), high quality excited state absorption spectra in this wavelength range were recorded, but comparison with the canonical DIB spectrum in Jenniskens & Désert (1994) again showed no correspondence existing between the two. However, in a subsequent (VUV/visible) double-resonance study (Ubachs, Hinnen, & Reinhold 1997), five transitions originating from the lowest rotational levels of the $C^1\Pi$ v=5 and v=6 states of H_2 *were* found to have the same frequencies and line widths as some weak narrow DIBs. This at least marked the first time that *any* DIBs could actually be assigned to transitions measured in gas-phase molecules that are known to exist in interstellar space.

In 1998 the authors were invited to present the current status of their H_2 DIBs model at the 109^{th} Faraday Discussions. [The title of this symposium was *Chemistry and Physics of Molecules and Grains in Space.* The published proceedings contain both the invited papers and the General Discussions that followed presentations of the former. Hereafter we will let III represent both our invited paper (Sorokin, Glownia, & Ubachs 1998) and the General Discussion that followed its presentation.] From III, one can gather that by 1998 one main change in the H_2 DIBs model had occurred. By 1998 the present authors had prepared a computer-generated table (unpublished) showing that 187 *distinct* DIBs listed in Table 3 of Jenniskens & Désert (1994) could be assigned to dipole-allowed transitions between *bound* H_2 excited states, with the *precisely known* (the result of decades of research by the Meudon and other world-famous spectroscopic groups – those studies that have been particularly essential for our work being referenced in III) H_2 transition frequency in each case falling within the margin of error for the DIB frequency listed in Table 3 of Jenniskens & Désert (1994). The main reason that the number of DIB coincidences with H_2 excited state transitions had by 1998 increased from the 70 reported in II was that in 1998 both singlet *ungerade* and singlet *gerade* H_2 levels were considered as possible lower levels for H_2 transitions assigned to DIBs. The 187 DIBs that were assigned included both those that were narrow and those that were broad. Of course, one would expect that broad DIBs would lead to multiple assignments, and this was indeed found to be the case. For example, the strongest DIB by far – the one at 4429 Å – has seven different assignments in our 1998 table of DIB coincidences with transitions between bound excited state levels of H_2. In three of these assignments, the lower H_2 level is a singlet *ungerade* level. In the other four, it is a singlet *gerade* level. The diagram in Fig 24 of III shows one of the latter assignments - one which we believed at the time to be the most likely explanation for this particular DIB. However, as will be seen in Sect. 3, we now actually favor an assignment for λ4429 in which the lower level(s) of the coincident H_2 transition(s) are B-state levels in J'=0,1, and 2 (*i.e.* bound singlet *ungerade* levels), but in which there is only *one* upper level - a single *unbound* (*i.e. dissociative*) state of H_2!

While in III it was again noted that all the H_2 DIB assignments made up to that point strongly implied that a highly selective form of H_2 photoexcitation must be occurring, the authors were still unable to suggest a photonic model which could convincingly explain how this could take place. Throughout III the authors actually invoked the same basic model that was employed in II – *i.e.* one involving SRS processes pumped by greatly enhanced photon densities of starlight spectrally centered at the strongest H_2 resonance line frequencies. For the same reasons that were outlined above, this unfortunately makes most of the theoretical discussion contained in III invalid.

One more paper focusing on both the DIBs and on the so-called "unidentified infrared emission bands" (UIBs) was published by the authors in 2000 (Sorokin & Glownia 2000). Here again it was postulated that the combined effects of elastic scattering and diffusion would lead to enormous photon density enhancements – in this case at the Ly-α wavelength. The Ly-α was assumed to be generated via H^+-electron recombination occurring within a Strömgren sphere – *i.e.* exactly the same process invoked in I. Emerging from the Strömgren sphere, the Ly-α radiation in the model becomes enhanced in the surrounding neutral PDR via the same basic photon trapping process invoked in II and III, with the scatterers in this case being H atoms. A Ly-α photon density enhancement factor of 10,000 was assumed to result. Clearly, after the passage of five years since the publication of I, novel nonlinear-optics-based ideas that might possibly be used to account for strong, selective photoexcitation of H_2 were no longer occurring to the authors, nor apparently to anyone else. It is thus perhaps understandable why no references to the basic idea that H_2 might be the carrier of the DIBs have appeared in the scientific literature during the past five years.

Very recently, the authors have proposed a new theory (Sorokin & Glownia 2005, hereafter referred to as paper IV) [1] applicable to another field of astrophysics – that which concerns line-driven stellar winds. In this theory, line-driven acceleration of select species ions in the stellar winds of OB-type stars can occur via the nonlinear process of stimulated Rayleigh scattering. In the model describing the latter process, radially-outwards-directed acceleration of an ion species possessing a strongly-allowed resonance transition at ν_o occurs simul-

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[1] http://domino.watson.ibm.com/library/cyberdig.nsf/papers/
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taneously with generation of intense, highly monochromatic, radially-inwards-propagating, coherent light at this same frequency, with continuum light from the star over a wide spectral range (*blueshifted* with respect to ν_o) providing the necessary pump power to drive the stimulated process. Because an inherent feature of the nonlinear line-driven stellar winds model is generation of intense monochromatic coherent light at the rest frame resonance frequencies of whatever ion species are being accelerated, we have now with renewed interest begun to explore whether this model might be modified in some manner so as to provide a rational basis for postulating that intense resonant coherent light could also be present in a neutral-hydrogen-containing PDR located close to an illuminating star. Any success in this direction should have the effect of reawakening interest in the idea that H_2 is the carrier of the DIBs, since, as explained at length above, our inability over the past ten years to suggest a *physically credible* mechanism through which selective photoexcitation of H_2 could occur most likely has been the main reason the H_2 DIBs model has fallen into complete oblivion over the past five years. In the present paper, we report on initial steps we have taken in this new effort.

To try to explain how DIBs could originate, we have modified the nonlinear line-driven stellar winds model of IV as follows. Replacing the strong, ionized OB stellar wind assumed in IV are H_2 molecules and H atoms located in a neutral PDR close to the photosphere of a bright illuminating star. It is assumed that the ionized H II region lying between the star's photosphere and the PDR is comparatively thin, *i.e.* that there is not present a large-radius Strömgren sphere. A thin H II region would characterize an illuminating star enveloped by a dense cloud containing relatively high densities of neutral hydrogen. Such a situation could be expected to exist in the case of a newly formed star, for example.

In the modified model, both H_2 molecules and H atoms in the PDR become nonlinearly accelerated radially outwards from the star via the same line-driven stimulated Rayleigh scattering mechanism proposed in IV, and concomitant generation of intense, radially-inwards-propagating, relatively monochromatic coherent light occurs at Ly-α and at the frequencies of strong VUV absorption lines of H_2 which lie in a spectral region where intense continuum light from the star reaches the PDR.

However, unlike what happens to ions in a strong OB-type stellar wind, the accelerations received by both the H_2 molecules and H atoms in the modified model are not sufficient to allow their escape from the star's gravitational field, and they eventually fall back to the base of the PDR. As the neutral hydrogen particles approach the latter, they become *decelerated* by the same stimulated Rayleigh scattering process that accelerated them radially outwards - this time, however, with *redshifted* continuum light from the star being absorbed. Again, intense monochromatic laser light aimed at the star at Ly-α and at select H_2 frequencies is concomitantly produced. In the modified model, this cycling of H_2 molecules and H atoms is continually repeated, with no loss (or gain) of neutral hydrogen particles occurring. With a rational and physically sound basis thus provided for postulating the presence within a PDR of intense, relatively monochromatic, coherent VUV radiation at Ly-α and at specified H_2 frequencies, it becomes much simpler both to identify - and to justify - those nonlinear photonic mechanisms which should lead to selective absorption occurring at DIB frequencies on transitions between H_2 excited states. Furthermore, on the basis of the dynamic PDR model here postulated, it will be shown below that one can (via the Doppler effect) now plausibly account for the random juxtaposition of broad and narrow DIBs that occurs throughout the entire DIB spectrum. In essence, this arises because H_2 molecules in levels with different rotational quantum numbers become nonlinearly accelerated/decelerated by different amounts.

One other important difference exists between the dynamic PDR model of the present paper and the nonlinear line-driven stellar winds model of IV. In the latter, nonlinear acceleration of select species ions was assumed to commence at the photospheric surfaces of OB-type stars, and to continue radially outwards in the stellar winds. The initial nonlinear acceleration received by the ions was hypothesized to be great enough to allow their radially-outwards-directed motions to be completely decoupled from Coulombic interactions with the far more abundant field particles (*i.e.* protons, He^{2+} ions, and electrons) of the fully ionized stellar winds. In the model of IV, the nonlinearly accelerated ions were in effect able to become "run away" ions, reaching radial velocities in particularly hot stars as high as $c/100$ before escaping into interstellar space. In IV the effect of the star's gravitational field was entirely neglected. By contrast, in the model of the present paper there is no Coulombic coupling interaction to slow down the neutral particles being accelerated.

The present paper is organized in a somewhat unusual manner. As the basic physics underlying the stimulated Rayleigh scattering process was thoroughly explained in IV, it will not here be repeated, except in brief outline. This is done in Sect. 2. With a relatively sound basis having been provided for postulating that intense coherent light is generated in the PDR at select H_2 absorption line frequencies, one can next logically deduce that, when a number of conditions are satisfied, stimulated Raman scattering (SRS) processes could also in principle be induced to occur in the PDR model. This is briefly outlined in Sect. 2.

The authors have noted that archived *Far Ultraviolet Spectroscopic Explorer (FUSE)* absorption spectra in the range 917-1180 Å are available for three of the stars shown in Fig. 1. Since this wavelength range encompasses the H_2 transitions at which one would expect stimulated Rayleigh scattering to occur in the dynamic PDR model being proposed, these spectra are examined in Sect. 3 for hints that such nonlinear scattering processes may indeed be occurring. A few unusual spectral features (*e.g.* definite P Cygni profiles) are noted which to us strongly suggest that nonlinear accelerations of H_2 molecules are indeed occurring. On the basis of the dynamic PDR model, we also offer an admittedly highly speculative – yet exciting and seemingly quite plausible - new interpretation for the famous λ2190 "bump" that often is present in the interstellar extinction curve measured in a given line-of-sight. Astronomers have long noted that a positive correlation exists between DIB strength and the λ2190 feature. For example, in a large sample of stars, Wu, York, & Snow (1981) found that the depth of the λ4429 DIB correlated with the depth of the λ2190 feature just as well as it did with E(B-V) reddening observed in the same line-of-sight. The λ2190 feature is very strongly present in *all* the stars of Fig. 1. In Sect. 3 it is further suggested that, via basically the same photonic mechanism hypothesized to produce this feature, those very broad and very strong DIBs (*e.g.* λ4429) observed in the near–UV to green spectral region could also be produced.

In Sect. 4, we test the dynamic PDR model to see if it can plausibly account for the observed features of λ7224 - a major, very well characterized DIB, which is both sharp and possesses a large equivalent width. It is the present opinion of the authors that this assignment affords striking additional evidence supporting both the dynamic PDR model and the hypothesis that H_2 is the carrier of the DIBs.

2. Stimulated Rayleigh scattering processes occurring in the dynamic PDR model

As explained above, stimulated Rayleigh scattering is envisioned to be the means by which intense laser light is generated in the dynamic PDR model here being proposed. This process is basically the same as the stellar winds nonlinear ion acceleration mechanism proposed in IV. However, it is here hypothesized that intense coherent light is generated at the frequencies of *several* strong H_2 absorption lines – mostly R(0), R(1), P(1), and Q(1) transitions. In the unit step of the stimulated Rayleigh scattering process that would occur on B4-0R1, for example, an (X0, J''=1) H_2 molecule moving away from the illuminating star with *radial* velocity v becomes nonlinearly accelerated, with the following quantum-mechanical exchanges of energy occurring *simultaneously.* (1) The H_2 molecule absorbs a photon from the illuminating star's continuum at some frequency ν_1 (measured in the rest frame of the *star*) located in the spectral vicinity of the B4-0R1 transition frequency ν_o = 95241.38 cm^{-1}. (2) At the same time, the H_2 molecule emits a photon at ν_o (measured in the rest frame of the *star*) radially inwards (*i.e.* towards the star), adding to the intensity of a spherically symmetrical, radially-inwards-propagating, monochromatic light wave at ν_o

(measured in the rest frame of the *star*) that is already present at the position of the H_2 molecule. (3) As a result of (1) and (2), the radial velocity v of the H_2 molecule becomes increased by an amount Δv. We now repeat the simple argument presented in IV showing that the values of ν_1 and Δv are here completely determined by requiring that both energy and momentum be conserved in the unit nonlinear scattering step.

Requiring that energy be conserved in the unit scattering step implies that

$$h\nu_1 \cong h\nu_o + m_{H_2} v(\Delta v), \tag{1}$$

while requiring that momentum be conserved dictates that

$$\frac{h\nu_1}{c} + \frac{h\nu_o}{c} = m_{H_2}(\Delta v). \tag{2}$$

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

$$\Delta v \approx 2h\nu_o / c m_{H_2}. \tag{4}$$

As extensively discussed in IV, the spherically symmetric, monochromatic light wave at ν_o would here become enormously amplified in stimulating the nonlinear scattering process as it propagates radially inwards towards the star, all the while retaining a relatively high degree of monochromaticity. [For analytical purposes, this light wave is termed the ν_2 wave. Its flux (photons cm^{-2} sec^{-1}) is denoted by ϕ_2.] Nonlinear absorption of continuum light, induced by the presence of the ν_2 wave, would both pump the stimulated scattering process and lead to the formation of a spectrally-wide region of continuum absorption originating at ν_o and extending to higher frequencies. The growth of the ν_2 wave with radial distance r from the center of the star is shown in IV to be given by the equation:

$$-\frac{d\phi_2(r)}{dr} = \sigma_{nl}(r) n_{0,1}(r) \Psi_1(r) \phi_2(r), \tag{5}$$

where the three dependent variables [aside from $\phi_2(r)$] are as follows. The quantity $\Psi_1(r)$ is the stellar continuum flux *per unit frequency width* (photons cm^{-2} sec^{-1} per c.p.s. $\equiv$ photons cm^{-2}) in the spectral vicinity of ν_o. The quantity $n_{0,1}(r)$ is the density of H_2 molecules in (X0, J''=1) at position r. The quantity $\sigma_{nl}(r)$ is the cross-section (units cm^4) for the nonlinear scattering process. An explicit formula for $\sigma_{nl}(r)$ is given below. Postulating the quantities $\phi_2, \Psi_1, n_{0,1}, \sigma_{nl}$ (as well as the radial velocity v) to be single-valued functions of r is done in the interests of mathematical simplicity. It should not strongly affect the physics of the problem.

As shown in IV, the stimulated Rayleigh scattering process characterized by the unit step under consideration would have a nonlinear scattering cross-section $\sigma_{nl}(r)$ given by the simple expression:

$$\sigma_{nl}(r) = \frac{8\pi^4 e^4 x^4_{B4-0R1}}{h^2 \left[v^2(r)\right]}, \tag{6}$$

where x_{B4-0R1} is the transition moment for the B4-0R1 transition, and $v(r)$ is the radial velocity of H_2 (X0, J''=1) molecules at position r. The probability per unit time that an H_2 (X0, J''=1) molecule moving in the PDR with radial velocity $v(r)$ undergoes the unit nonlinear scattering step under consideration is

$$(t.p.)_{stim} = \sigma_{nl}(r)\phi_2(r)\Psi_1(r). \tag{7}$$

One sees from Eqs. (6) and (7) that, as the positive radial velocities of the H_2(X0, J''=1) molecules become larger, the probability that the molecules will continue to be nonlinearly accelerated rapidly decreases. Eventually, under the influence of the star's gravitational field, the outward motion of each molecule must cease, and the molecule must start to fall back radially towards the star. However, as the molecule approaches the base of the PDR, it begins to become *decelerated* by the exact same nonlinear scattering mechanism that originally propelled it outwards. During the deceleration process, an inwardly-propagating, spherically symmetric, coherent light wave at ν_o is again produced. However, the pump power which drives the deceleration process now comes from stellar continuum photons that are *redshifted* with respect to ν_o. Therefore, according to the model assumed in the present paper, one would expect absorption of continuum light from the star occurring as an integral part of the nonlinear acceleration/deceleration process to produce a roughly *symmetrical* spectrum about ν_o. This again represents another major difference between the present model and that of IV.

There are two key features of the nonlinear scattering mechanism which should help reestablish credibility for the basic idea that H_2 might be the carrier of the DIBs. Most important is the fact that the mechanism provides a rational basis for assuming the presence in the PDR of spherically symmetric, radially-inwards-propagating, *high-intensity* laser light at select H_2 frequencies. This effectively allows one to discard completely the untenable hypothesis made in II and III that, via elastic scattering and diffusion, significant enhancement of starlight photon density could occur in the PDR at frequencies close to that of an H_2 absorption line.

The other key feature is that the radial velocities of the nonlinearly accelerated/decelerated H_2 molecules in a given X0 rotational level [*e.g.* (X0, J''=1)] in the PDR would span a very much *wider range* than that which would arise from motions of thermally equilibrated H_2 molecules. Moreover, this range would be different for molecules in different rotational levels. It is on the basis of this second feature that one can begin to speculate why DIBs with greatly varying line widths appear intermixed throughout almost the entire DIB spectrum. Since this is clearly a very important aspect of the dynamic PDR model, we now discuss this effect more fully.

As just explained, hydrogen molecules in (X0, J''=1) will be radially accelerated/decelerated in the dynamic PDR by the stimulated Rayleigh scattering mechanism associated with the B4-0R1 resonance. Moreover, each H_2 (X0, J''=1) molecule in the PDR additionally will be radially accelerated/decelerated via stimulated Rayleigh scattering processes occurring on other transitions involving (X0, J''=1), *e.g.* B4-0P1, B3-0R1, B3-0P1, C0-0R1, C0-0Q1, ... etc. As each H_2 (X0, J''=1) molecule travels up and down through the PDR, the value of its radial velocity will cycle between near 0 (the minimum velocity, attained both at the base of the PDR and at the highest point in its trajectory) to $\pm v_{\rm max}$(the maximum velocity, attained by the molecule both during the upwards-directed and downwards-directed segments of its trajectory through the PDR). According to Eq. (3), if stimulated Rayleigh scattering is occurring on a specific transition (*e.g.* B4-0R1), one should be able to estimate roughly the maximum upwards-directed velocity $v_{\rm max}$ from the expression $v_{\rm max} = [c(\nu_B - \nu_o)]/2\nu_o$, where ν_B is the bluest frequency of the nonlinear absorption region about ν_o. [More subtle considerations – which we here for simplicity forego – are required in the (likely) event that *even more intense* stimulated Rayleigh scattering is occurring on other transitions (*e.g.* $B5-0R1$) involving (X0, J''=1).]

However, H_2 molecules in (X0, J''=2), (X0, J''=3), and (X0, J''=4) will be much less accelerated by the nonlinear scattering process. The basic reason for this is that there are far fewer molecules in these levels than there are in (X0, J''=0) and (X0, J''=1). This makes the optical gain much less for generated ν_2 waves associated with higher-J'' levels. With smaller fluxes ϕ_2 for ν_2 waves, the nonlinear accelerations will be less. The VUV H_2 spectra shown in the following section suggest that H_2 molecules in (X0, J''=2) are definitely accelerated, although much less than those in (X0, J''=0) and (X0, J''=1). Those in (X0, J''=3) are accelerated still less than those in (X0, J''=2), while those in (X0, J''=4) show no evidence of being accelerated at all. All told, there evidently should be a wide distribution of radial velocities for H_2 molecules in the PDR in the five lowest rotational levels of X0. Roughly speaking, therefore, broader DIBs should result from nonlinear photonic excitation of X0 molecules in J''=0 and J''=1. DIBs of medium width would be formed when molecules in, say, (X0, J''=2) are nonlinearly excited. An acceptable assignment of a relatively very narrow DIB must involve nonlinear excitation of (X0, J''=4) molecules. In Sect. 4, such an assignment will be discussed.

In the dynamic PDR model, it is assumed that intense, relatively monochromatic, radially-inwards-propagating, coherent light is generated at several specified H_2 frequencies via stimulated Rayleigh scattering. If this is indeed the case, it should also be possible for intense coherent light to be generated via stimulated Raman scattering (SRS), with the pump light being the former. However, for SRS to occur, several conditions would have to hold. (1) The H_2 level from which the SRS process originates (the *initial* level) must either be a level significantly thermally populated (*i.e.* X0, J''=0-4), or must be populated from another level by the action of intense, laser-like light. (2) The *terminal* level for the SRS process must either have some natural means by which the population accumulating in it via the SRS process can rapidly leak away (*e.g.* via strong spontaneous emission decay), or there must be a laser-like process that drives this population to another level. (3) The frequency of the SRS pump light must be nearly resonant with a strong transition originating from the SRS initial level. (4) The frequency of the SRS Stokes-wave light (*i.e.* the light generated by the SRS process) must be nearly resonant with the optical transition connecting the SRS terminal level with the upper level of the strong transition in (3). This transition near the Stokes-wave frequency should also be very strong.

3. Examining VUV spectra of DIB-containing stars and the λ2190 interstellar extinction feature for evidence supporting the dynamic PDR model

3.1. VUV spectra of DIB-containing stars

As noted in the Introduction, archived VUV spectra in the range 917 – 1180 Å are available for downloading on the *MAST Scrapbook* interactive web site for three of the stars shown in Fig. 1. Since this is the spectral region that should contain the frequencies of the intense coherent light that is hypothesized to be generated in the dynamic PDR model, one can reasonably inquire whether examination of these spectra can provide any evidence to support such a hypothesis. Of course, the main difficulty here is that the coherent light generated in the model are continuous, spherically symmetric, light waves that propagate radially inwards towards the star. The generated light is thus always directed away from the observer, and in principle can never directly be seen. Only secondary effects of the presence of stimulated Rayleigh scattering should be observable.

In all three *FUSE* spectra, the continuum light from the stars appears heavily attenuated by interstellar dust as one moves to shorter and shorter wavelengths. To simplify our analysis, we will here assume that most of this extinction occurs in the line-of-sight between the star-enveloping cloud of the dynamic PDR model and the observer – not between the cloud and the star's photosphere, *i.e.* not in the H II region of the star.

In all three *FUSE* spectra, one sees that light from the star is *completely* attenuated in wide spectral intervals that encompass the R0, R1, and P1 transitions of . . . B2-0, B3-0, B4-0, B5-0, . . . etc. Examples of this are shown in Figs. 2 and 3. In the dynamic PDR model, one expects light in exactly these spectral intervals to be absorbed in pumping the stimulated Rayleigh scattering processes that are hypothesized to occur. However, since light from the star would also be attenuated in these same spectral intervals via the process of linear absorption, it appears that one would here be at an impasse to try to find any evidence supporting the former.

To try to make some progress in our analysis of the VUV spectra, we will assume that the same dust cloud, which was postulated above to lie somewhere in deep interstellar space between the PDR and the observer, also contains a lot of *cold* H_2 gas. *All* the H_2 molecules in this interstellar dust cloud will be assumed to occupy the two lowest energy levels of parahydrogen and orthohydrogen, *i.e.* (X0, J''=0) and (X0, J''=1). For the moment we assume that all extinction in the above mentioned spectral intervals in which light from the stars is observed to be completely attenuated is the result of linear absorption. On the basis of this simple model, we are then allowed to postulate that any absorption lines in the VUV spectra seen originating from H_2 X0-state rotational levels $J'' \geqslant 2$ are the result of processes occurring in the star-enveloping PDR.

In Figs 2 and 3 one first notes that the B5-0P2 absorptions are definitely much *wider* than those of B5-0R3, B5-0P3, B5-0R4, and B5-0P4, not to mention the much weaker absorptions at B6-0P5 and B7-0R8 which, somewhat surprisingly, are also seen to be present. This is clearly what one would expect on the basis of the nonlinear PDR model, as explained in Sect. 2. However, the spectra in Figs. 2 and 3 actually contain dramatic features that the authors believe make a compelling case for the validity of this model. This will now be explained.

The above mentioned dramatic features are the strong *P Cygni profiles* clearly seen to be present on the B5-0R2 and B5-0P2 transitions in both Figs. 2 and 3. As discussed at length in IV, the appearance of a P Cygni profile in a star's spectrum is a signature of line-driven nonlinear acceleration occurring via the process of stimulated Rayleigh scattering. Space limitations do not allow us here to repeat the full analysis given in IV of the mechanism by which fluorescence peaks in P Cygni profiles are formed. Let us instead apply the dynamic PDR model to deduce roughly what the maximum outwards-propagating velocity attained by the H_2 (X0, J''=2) molecules would be in, say, the star HD 216898. (We consider the spectrum in Fig. 2, rather than the one in Fig. 3, because the signal-to-noise ratio is better in the former.)

We use the fact that the sharp B6-0P5 absorption (λ = 1040.06 Å) occurs in Fig. 2

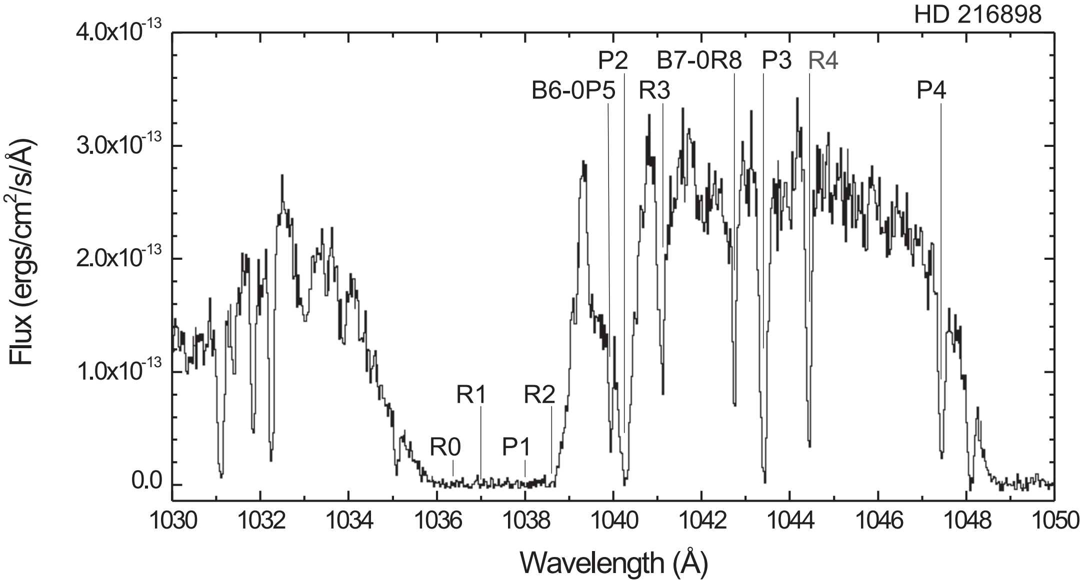

Fig. 2.— A portion of the *FUSE* spectrum of HD 216898, downloaded from the *MAST Scrapbook* interactive web site. Marked transitions are B5-0 unless indicated differently.

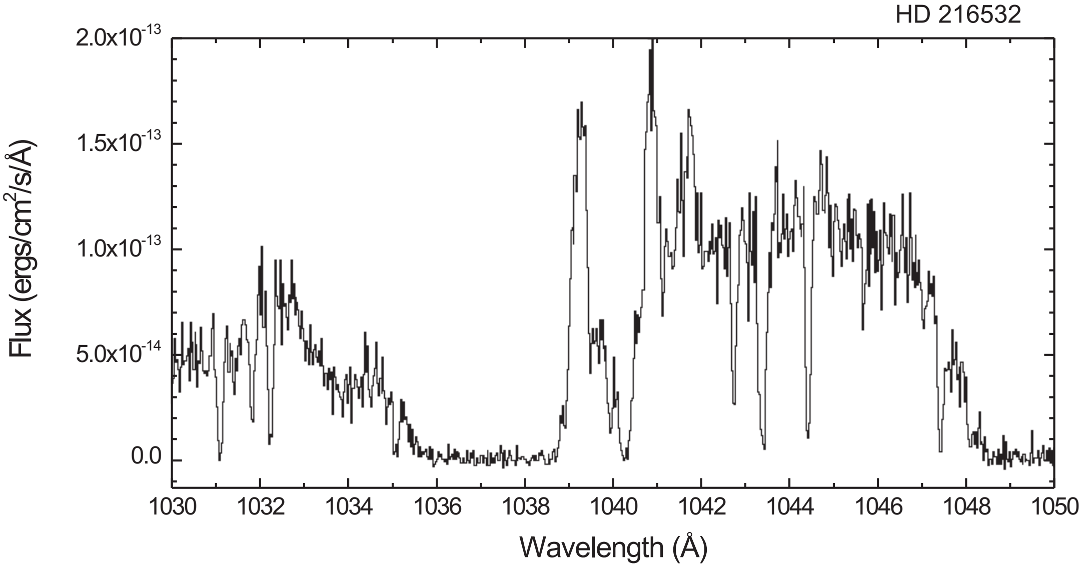

Fig. 3.— A portion of the *FUSE* spectrum of HD 216532, downloaded from the *MAST Scrapbook* interactive web site.

at 1039.95 Å to obtain an accurate wavelength calibration for the spectrum. The blue wavelength limit of the B5-0P2 P Cygni nonlinear absorption region occurs at about 1039.56 Å in Fig. 2, from which we deduce that the former is offset from the B5-0P2 resonance frequency ν_o = 96119.99 cm^{-1} by Δ =74.55 cm^{-1}. According to Eq. (3), one must divide Δ by 2 to get the maximum velocity $v_{\rm max}$. The result is 116 km/sec. At a wavelength of 5000 Å, this would correspond to a Doppler shift of 7.76 cm^{-1}. From this, one might suspect that the famous λ5780 and λ6284 DIBs, both of which have linewidths of this order, could arise from multiphoton excitation processes of H_2 molecules in (X0, J''=2), driven by intense coherent light generated via stimulated Rayleigh scattering.

From Figs. 2 and 3, one of course also deduces that intense coherent light is generated on B5-0R2. In the multiphoton excitation scheme (Fig. 6) proposed in Sect. 4 to account for the λ7224 DIB, it is assumed that intense coherent light is generated on B5-0R2.

For future explorations, one might profitably carefully examine the *FUSE* spectrum of the B3 Ia star HD 198478. This is a star with strong DIBs Herbig & Soderblom (1982) for which the *FUSE* spectrum appears not as heavily attenuated in going to shorter wavelengths as it is in the case of each O-type star in Fig. 1. The signal-to-noise ratio in the HD 198478 VUV spectrum is also better than in the spectra of the latter stars. Interestingly, the HD 198478 spectrum displays many more prominent P Cygni profiles than do the stars of Fig. 1. There are, for example, strong P Cygni profiles at B6-0R2, B6-0R3, B6-0R4, B5-0P2, B5-0R3, and B5-0P3 in this star.

3.2. The λ2190 interstellar extinction feature

On the basis of the dynamic PDR model, an interesting new interpretation can be offered for the famous λ2190 “bump” (Fig. 4) frequently appearing as the dominant interstellar extinction feature in lines-of-sight to stars. For years, astrophysicists have generally believed that this feature results from linear absorption or linear scattering of light by dust particles of some type, but the exact compositions of the latter remain undetermined. As noted in the Introduction, astronomers have also observed that DIB strength in a given line-of-sight generally correlates well with the strength of the λ2190 feature in the same line-of-sight. From archived spectra available on the *MAST Scrapbook* interactive web page, one can see that the λ2190 feature is indeed very strong in each of the six stars shown in Fig. 1.

In the new interpretation for the λ2190 absorption band here being proposed, the latter results from occurrence of strongly allowed, resonant, simultaneous two-photon absorptions by H_2 (X0, J'') molecules, driven by the intense laser light postulated in the present paper to be generated via stimulated Rayleigh scattering. The resonant intermediate-state levels for the two-photon absorption processes are the several B-state and C-state levels involved in the lasing. However, *one* H_2 state serves as the final state for all the individual two-photon absorption processes making up the $\lambda 2190$ band. This state is the doubly excited $^1\Pi_g(2p\sigma)(2p\pi)$ dissociative state shown in Fig. 5. Since the electronic configurations of the X state, the B state, and the C state are, respectively, $^1\Sigma_g^+(1s\sigma)^2$, $^1\Sigma_u^+(2p\sigma)(1s\sigma)$, and $^1\Pi_u(2p\pi)(1s\sigma)$, one sees that optical transitions to the doubly excited $^1\Pi_g(2p\sigma)(2p\pi)$ state from either B- or C-state levels are very strongly allowed. One thus should expect continuum light coming from the star to be strongly absorbed in the second steps of the two-photon transitions.

With use of the Franck-Condon approximation, one can roughly estimate what the center frequency of the absorbed light should be for an individual two-photon process contributing to the overall $\lambda 2190$ absorption band profile by drawing a vertical line upwards from the right-hand turning point of the B- or C-state vibrational level involved. This vertical line will intersect the dissociative $^1\Pi_g(2p\sigma)(2p\pi)$ state at a certain energy value. When one subtracts from this value the energy of the B- or C-state vibrational level, one determines the center frequency of the light that should be absorbed by the two-photon process. This absorption band should of course be greatly broadened by the fact that the upper state is dissociative.

Making use of both the B- and C-state potential energy tables given in Sharp (1971) and the detailed plot of the $^1\Pi_g(2p\sigma)(2p\pi)$ potential curve contained in Guberman (1983), we have roughly determined what the central wavelengths of the second steps of the two-photon transitions should be. They are plotted in Fig. 4. Interestingly, it is seen that the frequencies *are* distributed in a manner that is at least consistent with the hypothesis that the $\lambda 2190$ feature results from two-photon absorption by H_2 molecules.

In Guberman (1983), the $^1\Pi_g(2p\sigma)(2p\pi)$ potential curve is only plotted out to 4.4 a.u. (2.33 Å). The right-hand turning point for B6, for example, is at 2.53 Å. That for B10 is at 3.04 Å. This suggests that in the future it might be reasonable to examine whether any of the few *very broad* and *very strong* DIBs (*e.g.* $\lambda 4429$) appearing in the near-UV to green regions of the optical spectrum could result from the same photonic process just outlined. The fact that the equivalent widths of these broad DIBs generally greatly exceed those of most other DIBs would then have a simple explanation. Absorptions to the $^1\Pi_g(2p\sigma)(2p\pi)$ state originating from B6 to B10 levels would fall in the same general spectral region as the above-mentioned broad DIBs. One would expect these absorptions to be narrower than ones arising from B1 to B5, because the potential energy curve for the $^1\Pi_g(2p\sigma)(2p\pi)$ state presumably continually becomes less and less steep as it approaches its H(2l) +H(1s) limit. Therefore,

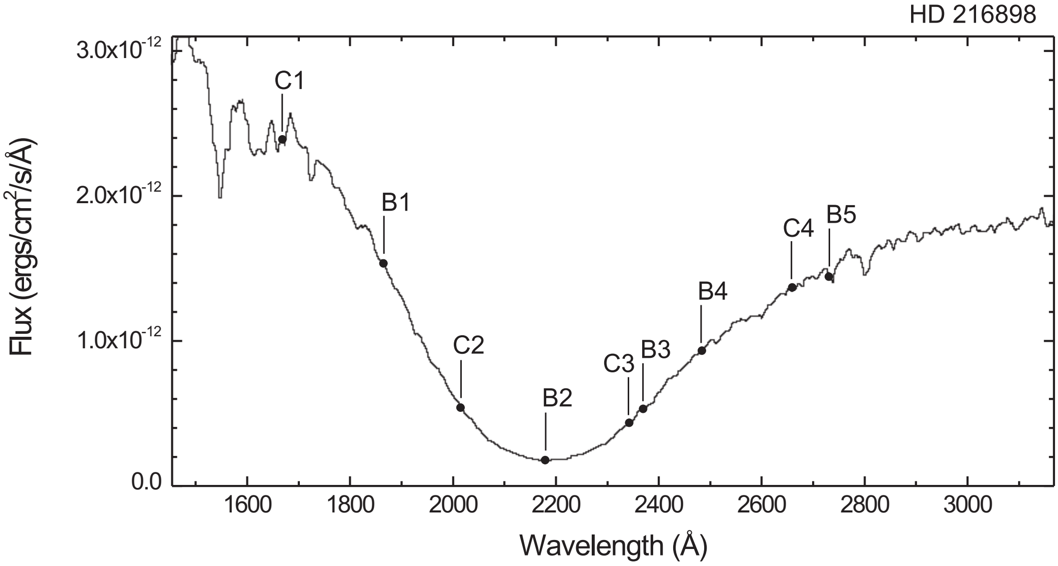

Fig. 4.— *WUPPE* spectrum of HD 216898, downloaded from the *MAST Scrapbook* interactive website. Predicted spectral locations of two-photon absorption band centers are superimposed (see text).

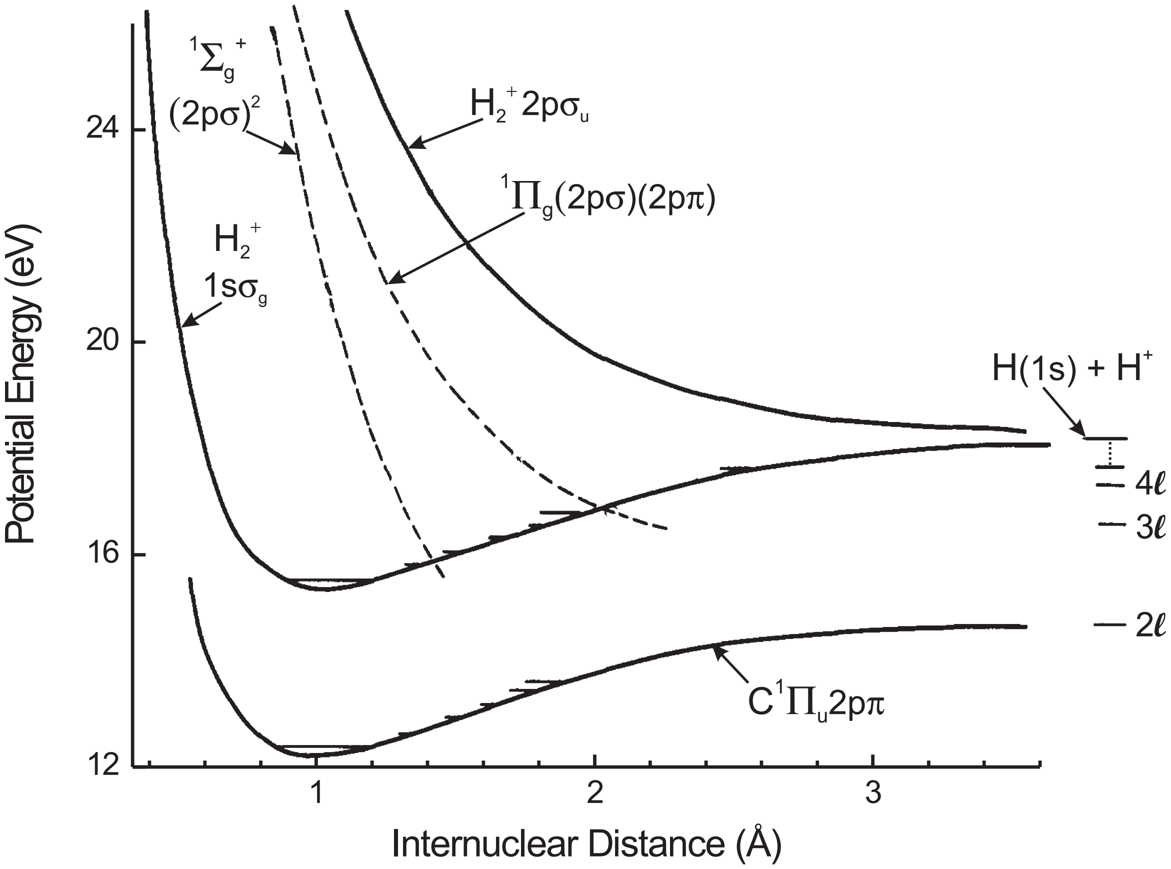

Fig. 5.— Potential curves for some excited states of H_2 and for two states of the ion H_2^+. Doubly excited states of H_2 are shown as dashed lines. Figure adapted from Chupka (1987), with permission.

the individual second step absorptions in this spectral region should be well separated from one another, resulting in the appearance of distinctly separate DIBs.

4. The λ7224 DIB

The peak absorption intensity of the rather remarkable λ7224 DIB exceeds those of all DIBs located at wavelengths longer than 6284 Å. The λ7224 DIB is, relatively speaking, a very sharp DIB, having a linewidth in the range 2-3 cm^{-1}. In Table A1 of Herbig (1995), the center wavelength is listed as 7224.01 ± 0.02 Å. In Table 3 of Jenniskens & Désert (1994), the center wavelength is listed as 7224.18 ± 0.21 Å. In our 1998 computer-generated list of coincidences existing between the frequencies of sharp H_2 transitions and those of DIBs, only one match appeared for λ7224. This involved the H_2 transition from (B11, J'=5) to (EF28, J=4). The calculated wavelength for this H_2 transition is 7224.03 Å. While this assignment itself correctly appears in Fig. 3 of the General Discussion that followed our presentation at the *Faraday Discussions No. 9* (*i.e.* the paper designated III in the Introduction), we now ask the reader to disregard entirely the complex photonic scheme shown in Fig. 3 of III by which it was suggested that level (B11, J'=5) could be optically excited. Instead, let us now direct our attention to Fig. 6, which diagrams how the λ7224 DIB could plausibly be formed on the basis of the dynamic PDR model.

From the comparatively very narrow width of the λ7224 DIB, it is at once apparent that the nonlinear photonic mechanism through which this DIB is formed must not *directly* involve photonic excitation of (X0, J''=0) molecules, because these would be strongly accelerated/decelerated via stimulated Rayleigh scattering, and Doppler broadening of all their optical transitions would occur as the (X0, J''=0) molecules fly up and down through the PDR. For the same reason, formation of the λ7224 DIB should not involve *direct* photonic excitation of (X0, J''=2) molecules, since clear evidence was presented in Sect. 3 that molecules in this level are accelerated/decelerated enough to result in Doppler shifts that at 7224 Å would be in excess of 5 cm^{-1}. By default, one must therefore consider nonlinear photoexcitation processes acting on (X0, J''=4) parahydrogen molecules.

Figure 6 diagrams a plausible scheme for nonlinear excitation of H_2 (X0, J''=4) molecules present in a dynamic PDR that should lead to visible continuum light emitted by the illuminating star strongly being absorbed at 7224 Å. The scheme shown involves successively linked SRS processes, driven by intense coherent light generated via stimulated Rayleigh scattering. We here note several features of this scheme, beginning our analysis at the level (X0, J''=4) from which the multiphoton unit process is assumed to originate.

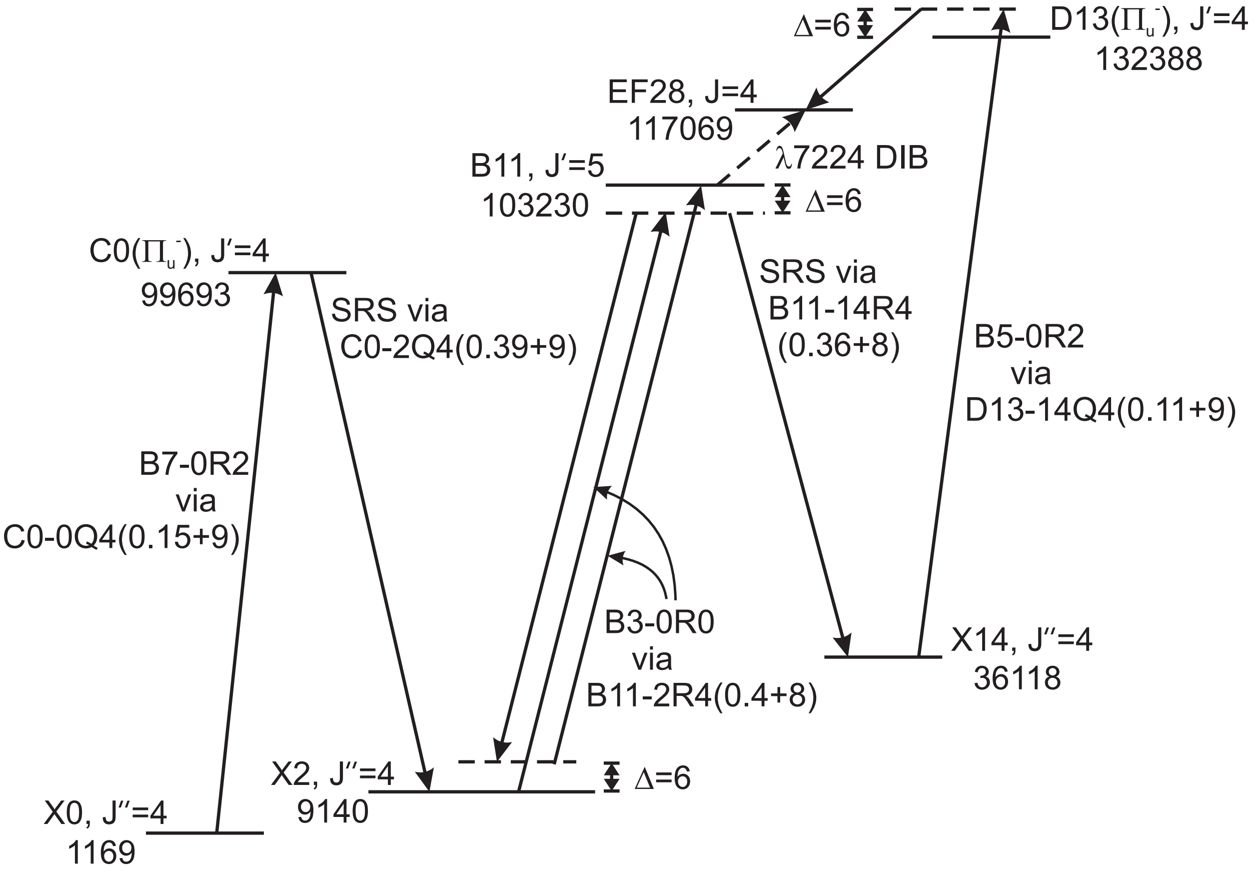

Fig. 6.— Multiphoton excitation scheme based upon the dynamic PDR model that should be capable of inducing absorption of starlight in a spectral band having properties very similar to those of the λ7224 DIB.

In the scheme of Fig. 6, the first SRS process is pumped by intense, radially-inwards-propagating, coherent light at B7-0R2, which one expects to be generated in the dynamic PDR model, according to the discussion that was presented in Sect. 3.1. Particularly noteworthy here is the fact that the transition frequency for B7-0R2 is *exactly* resonant with the very strong transition C0-0Q4 (both frequencies being 98524.37 cm^{-1}). This, together with the fact that the transition C0-2Q4 on which the SRS Stokes wave is generated is also very strong, combines to make the cross-section for the first SRS process extremely large. The SRS Stokes-wave radiation would also be generated as a spherically symmetric, radially-inwards-propagating, intense, coherent light wave, *i.e.* it would propagate in the same manner as the B7-0R2 wave that pumps it.

The first SRS process would quickly stop, if there were no means to deplete the terminal level (X2, J''=4). However, this is effectively accomplished by the second SRS process shown in the figure. This second SRS process is pumped by radially-inwardly-propagating coherent light at B3-0R0, with the latter expected to be generated via stimulated Rayleigh scattering even more intensely than B7-0R2. Again, the SRS process is very resonant, with the offset of the pump frequency from the transition to the real intermediate state (B11, J'=5) being only 6 cm^{-1}. Again, both transitions (B11-2R4 and B11-14R4) that determine the SRS cross-section are very strong. Again, the Stokes wave light generated spatially propagates in the same manner as the B3-0R0 pump light.

In Fig. 6, the terminal state (X14, J''=4) for the second SRS process is effectively depleted by a third SRS process, this one being pumped by intense coherent light generated via stimulated Rayleigh scattering on the transition B5-0R2, one of the transitions actually displaying P Cygni profiles in Figs. 2 and 3. Again, the pump frequency is very resonant (6 cm^{-1} offset) with a very strong transition (D13-14Q4) originating from the initial level (X14, J''=4) of the third SRS process. While the adiabatic transition moment (ATM) for the optical transition occurring between $(\mathrm{D13}(\Pi_u^-), J' = 4)$ and (EF 28, $J = 4$) has not been calculated, one can generally expect it to be quite high, because it should have roughly the same value (ATM = 0.5) as that for transitions occurring between levels of C12 and EF28. Enhancing the SRS cross-section here again is the fact that the generated Stokes-wave frequency ω_S is large (15325 cm^{-1}). Optical gain in an SRS process is proportional to ω_S.

Unlike the extremely metastable terminal levels (X2, J''=4) and (X14, J''=4) for the first two SRS processes shown in Fig. 6, the terminal level (EF 28, $J = 4$) for the third SRS process can decay via strongly allowed optical emission to many lower levels, and no additional laser source would therefore in principle be needed to deplete this level sufficiently to allow the SRS process to continue. However, one effect that the combined presence of the third SRS pump and Stokes waves in Fig. 6 would have is the following. If by some means the (B11, J'=5) level were to become populated, then the simultaneous presence of intense light at the third SRS pump and Stokes-wave frequencies would greatly enhance the probability that light emitted by the star could be absorbed at 7224 Å. One can logically postulate this to be the effect by which the λ7224 DIB is formed, but then a serious question arises concerning the exact photonic mechanism by which level (B11, J'=5) becomes populated. At this stage, one does not really know exactly how monochromatic the intense light generated by stimulated Rayleigh scattering at B3-0R0 could be. Even if the line width of this radiation were on the order of 10 cm^{-1}, and thus could spectrally overlap the B11-2R4 transition, only the process of elastic scattering could theoretically occur, because of the low gas densities present in the PDR. No H_2 molecules could be driven by this means into level (B11, J'=5). One thus seemingly has arrived at an impasse.

However, there *is* an elegant, nonlinear-optics-based, potential solution to the problem at hand. Because of the extremely resonant situation prevailing in Fig. 6, one can reasonably postulate that *another* type of stimulated scattering process - *stimulated hyper-Raman scattering (SHRS)* - also originates from level (X2, J''=4). This simultaneous three-photon process is indicated in Fig. 6. In the unit step of this process, two photons at ν_{B3-0R0} are absorbed, a photon at ($\nu_{B3-0R0} - 6$) cm^{-1} is created, and an H_2 molecule in (X2, J''=4) is driven to level (B11, J'=5). Thus, via a powerful nonlinear optics scheme, the striking λ7224 DIB absorption is created!

P.P.S. is grateful to IBM Research management for having allowed him retirement use of office and library facilities for the past four years. J.H.G. acknowledges partial support for this work through the Los Alamos National Lab LDRD-ER program.

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