H-atom laser without inversion (LWI) in space: a possible explanation for the intense, narrow-band, H(α) emission frequently observed in reddened early-type stars

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Abstract. A model is suggested to explain the frequently observed presence of intense, narrow-band, H(α) emission lines in the optical spectra of reddened, early-type stars (e.g. HD 44179, IRAS 18179-1346, IRAS 20298+4011). It is proposed that hydrogen atoms surrounding compact H II regions enveloping such stars become coherently phased via a nonlinear photonic mechanism that leads to ‘electromagnetically induced transparency (EIT)’. EIT is a powerful technique that can be used to make a material system transparent to resonant laser radiation, while still allowing large nonlinear resonant processes to occur with high probability. In EIT terminology, a ‘Λ’ configuration, involving H-atom levels (1s, 3p, and 2s), is here assumed to be operative. The EIT ‘coupling beam’ is the narrow-band H(α) radiation predicted to be coherently generated via a standard ‘laser without inversion (LWI)’ scenario when coherently phased atoms are excited to the 3p level by means of a separate nonlinear excitation process known as resonant hyper-Raman scattering (HRS). In the unit HRS pumping process, a pair of far-ultraviolet (FUV) photons, with frequencies lying very close to Ly-β but offset from it by equal amounts to high and low energies, are absorbed from the star’s blackbody continuum, a photon at Ly-β line center is emitted, and an atom is excited to the 3p level - with all events in this energy conserving process occurring simultaneously. The EIT ‘probe beam’ is the light predicted to be coherently generated at Ly-β line center, which - as a result of the complete linear transparency afforded at this frequency by the coherently phased H atoms - can propagate completely unattenuated through the optically thick H-atom cloud surrounding the star.

Key words: atomic processes – radiation mechanisms: non-thermal – stars: early type – stars: individual: HD 44179 – stars: individual: RR Tel – ISM: lines and bands

1. Introduction

The introduction of an entirely new concept to explain a class of observed phenomena in any field of science would seem to be a redundant activity, if the phenomena can reasonably be accounted for with use of existing theories and models. However, in the cases of certain astronomical observations of H(α) emission, standard explanations appear to be inadequate. This letter focusses specifically on recorded observations of intense H(α) emission in reddened early-type stars. It will be shown below that enough spectral information exists for such stars to suggest strongly that a new paradigm is here needed.

One that appears to be quite suitable for explaining the H(α) emission data was recently developed in the field of quantum electronics and is termed ‘laser without inversion (LWI)’. The LWI concept is itself inseparably tied to another recently developed quantum electronics concept, that of ‘electromagnetically induced transparency (EIT)’. In the present letter a novel astrophysical model based upon LWI/EIT is introduced that appears to be fully capable of explaining the most intense and spectrally narrowest H(α) emissions seen in reddened early-type stars.

2. H(α) emissions in reddened early-type stars

In Rawlings et al. (2000) new optical spectroscopy for 45% of an older catalog (Stephenson 1992) of ~440 reddened stars was performed in an attempt to isolate reddened stars which are also early-type. The spectra between 6100 Å and 6900 Å of all the stars studied are shown in Rawlings et al. (2000). Only fifteen of the stars surveyed could be classified as early-type stars. With regard to H(α), the spectra of these early-type stars show tremendous variations. Some (Fig. 4a) show H(α) only in absorption. Others (Figs. 4b, 4c, 4d) show H(α) strongly in emission, with an intensity completely disproportionate to all other absorption features present. Yet the spectral types of these stars are all apparently roughly comparable. In the spectra of all the cooler stars surveyed by Rawlings et al. (2000), H(α), if present at all, appears only in absorption.

Much spectral data exists for the star, HD 44179, that powers the fascinating Red Rectangle nebula. We here consider an apertured line-of-sight that includes just the star, not the nebula. In such a line-of-sight, one sees (Co-
Fig. 1. a-d. Spectra of three reddened early-type stars selected from Fig. 4 of Rawlings et al. (2000). Features labeled ‘d’ and ‘t’ are diffuse interstellar and telluric features, respectively. Stars labeled by running numbers used in Table 1 of Stephenson (1992). (StRS ≡ ‘Stephenson Reddened Star’.) Standard identifications for StRS 177 and StRS 368 are IRAS 18179-1346 and IRAS 20298+4011, respectively.

Fig. 2. STIS scan of HD 44179 taken on Mar 26, 1998 (T. Gull, principal investigator). Spectrum obtained from HST web archive.

In view of the enormous variations in H(α) spectral width and intensity observed in lines-of-sight to reddened stars of roughly the same spectral type, a non-stellar origin for this emission is strongly suggested. Hence - at least in the most singular cases - this emission must originate from H atoms located outside the photosphere of the illuminating star. If the H(α) emissions resulted from electron impact excitation occurring in compact H II regions about the stars, one would expect also to detect emissions at the wavelengths of H(β), H(γ), H(δ), etc.. At least in the case of HD 44179, these are not observed. H(α) emission could reasonably be produced via linear photoexcitation of H atoms located in neutral regions bordering H II regions. However, as discussed below, this would generally result in broadened H(α) emission-line profiles, and cannot account for the extreme δ-function-like profiles observed in some lines-of-sight. In essence, then, the nonlinear photoexcitation model introduced here will attempt to explain why some reddened early-type stars show H(α) emissions that are comparatively broad, particularly at the base, while others (e.g. Fig. 1b) display ones that are much sharper, more intense, and more singular-looking (i.e. unaccompanied by a significant pedestal).

3. Electromagnetically induced transparency (EIT)

To understand the concept of LWI, one must first understand that of EIT, since the former is built upon the latter. A good introductory review describing some of the recent exciting developments in EIT is Harris (1997). The particular LWI/EIT model being considered in the present letter involves the so-called three-level Λ scheme shown in Fig. 3. Transitions 1⇒3 and 2⇒3 are allowed; the total radiative decay rate of quantum level |3⟩ is Γ₃. Transition 1⇒2 is assumed to be basically forbidden. For H atoms, |2⟩ decays radiatively to |1⟩ via spontaneous two-photon emission at a rate ≈ 8 sec⁻¹. This degree of metastability
Fig. 4. Absorption (Im $\chi^{(1)}$) as a function of normalized probe frequency offset from $\omega_{13}$, in the absence and in the presence of a monochromatic coupling field tuned to $\omega_{23}$. From Fig. 2 of Harris et al. (1990).

qualifies the H-atom 2s level to be level [2] in a $\Lambda$-type EIT scheme.

When a nearly monochromatic laser beam (the EIT ‘coupling beam’), tuned to the center frequency $\omega_{23}$ of the $2 \leftrightarrow 3$ transition, is applied to a gas of three-level atoms, a sharp dip in absorption in the vicinity of the $1 \leftrightarrow 3$ transition occurs (Fig. 3). This cancellation in the imaginary part of the linear susceptibility (absorption is proportional to Im $\chi^{(1)}$) can be shown to arise from quantum interference. For the ideal case $\Gamma_3 = 0$, there is perfect transparency at the minimum. The width of the transparency hole varies as $\Omega_{23}$, the so-called Rabi frequency, which is itself proportional to the square root of the laser power ($\hbar \Omega = \mu E$, where $\mu$ is the dipole matrix element and $E$ is the optical field).

If another nearly monochromatic laser beam (the EIT ‘probe beam’), tuned to the center frequency $\omega_{13}$ of the $1 \leftrightarrow 3$ transition, is applied to the same gas of atoms, the system will quickly adjust itself so that there is also no absorption about the line center of the $2 \leftrightarrow 3$ transition. This occurs independently of the ratio of Rabi frequencies $\Omega_{13}/\Omega_{23}$. The two laser beams rapidly drive all atoms of the system into a stable ‘coherently trapped population state’. In this state, the wavefunction of all the atoms in the gas becomes an antisymmetric linear combination of the unperturbed wavefunctions of levels [1] and [2]. In this state, no atoms are present in level [3]. One of the earliest experiments in which coherent trapping of atomic populations was realized is described in Gray et al. (1978). Atoms coherently trapped by this method are also commonly referred to as ‘coherently phased’ atoms. The coherently trapped state is sometimes denoted by NC, standing for ‘non-coupled’, because Im $\chi^{(1)} = 0$ at the line centers of the two transitions $1 \leftrightarrow 3$ and $2 \leftrightarrow 3$. Once all the atoms of a gas have been driven to the NC state, light at the two applied laser frequencies can continue to pass over the atoms without being attenuated. There is a state orthogonal to the NC state in which the wavefunction of the atoms is a symmetric linear combination of the unperturbed wavefunctions of levels [1] and [2]. Because Im $\chi^{(1)} \neq 0$ at the two allowed transitions for atoms in this state, it is sometimes referred to as the C (‘coupled’) state.

4. Laser without inversion (LWI); pumping via hyper-Raman scattering (HRS)

Consider a $\Lambda$-type system with all atoms maintained in the NC state via the EIT process described above. If, through some separate means, some of these atoms can be excited to level [3], then these atoms can fluoresce at both $1 \leftrightarrow 3$ and $2 \leftrightarrow 3$ line centers via allowed transitions to the two C states shown in Fig. 3. Since the EIT mechanism rapidly and continually transfers all atoms from the C state to the NC state, true population inversions can exist between level [3] and both C states. Gain can therefore be present on these transitions, and stimulated emission (i.e. laser action) can result. This scenario is termed a ‘laser without inversion’, because there are many more atoms in each of the two NC levels than in level [3]. An LWI demonstrated by the group of M.O. Scully (Padmabandu et al. 1996) works by combining optical pumping and EIT.

In considering mechanisms that could pump an H-atom LWI in space, one first should analyze simple linear photoexcitation of NC atoms via absorption of far-ultraviolet (FUV) continuum light from the star in the spectral vicinity of Ly-$\beta$. Typical H-atom densities in cold, neutral clouds surrounding bright stars are $10^{-7}$–$10^{-5}$ cm$^{-3}$, implying collision rates $\sim$10$^{-8}$–$10^{-7}$ sec$^{-1}$. Such media should therefore be regarded as being virtually collisionless. In a collisionless regime, FUV light in the vicinity of Ly-$\beta$ - but offset enough from it to avoid the $\chi^{(1)}$ minimum (Fig. 3) - will either be elastically scattered by NC atoms or will undergo spontaneous resonant Raman scattering. In the latter process, an atom becomes excited to the NC [2] level, and a photon slightly offset from H($\alpha$) is simultaneously emitted. However, no excitation of level [3] occurs (Loudon 2000). Linear photoexcitation would therefore be an ineffective pumping mechanism for LWI in space, but it could perhaps account for the presence of spectrally broad H($\alpha$) emissions seen from some reddened early-type stars.

Harris et al. (1990) were the first to show that, while EIT makes a material system transparent to resonant laser radiation, it nonetheless allows a large nonlinear resonant process to occur with high probability. We propose that one such process, resonant hyper-Raman scattering (HRS), might be a viable mechanism for pumping an H-atom LWI in space. In the unit HRS pumping process (Fig. 4), a pair of FUV photons, with frequencies lying very close to Ly-$\beta$ but offset from it by equal amounts to...
Fig. 5. Resonant hyper-Raman scattering process proposed in text as the pumping mechanism for an H-atom LWI.

high and low energies, are absorbed from the star’s blackbody continuum, a photon at Ly-β line center is emitted, and an NC atom is excited to level $|3\rangle$ - with all events in this energy conserving process occurring simultaneously. This HRS mechanism would be an efficient H-atom LWI pump, since, in the unit process, both a Ly-β photon at line center is generated, and an NC atom is excited to the desired $3p$ level. An important feature of LWI excitation occurring via this mechanism is that the rate of pumping is itself proportional to the intensity of the radiation present at Ly-β line center.

5. H-atom LWI associated with a reddened, early-type star

One would expect an H-atom LWI associated with a reddened early-type star to occur in a thin shell of neutral gas located just outside an ionized hydrogen (H II) region. For a B0 III star, the radius $R_S$ of such a region would typically be ~0.01 pc. At 1000 Å, the FUV continuum flux at $R_S$ propagating outward from the star would be ~3 x 10^{10} photons per cm$^2$ per sec per wavenumber. This flux could be additionally enhanced several hundred times around the wavelength of Ly-β via photoprocesses occurring in the H II region. It is also possible that nonlinear elastic scattering by H atoms of the two LWI narrow-band emissions generated would lead to additional intensity enhancement of these emissions in the active region via the effect of decreased spatial diffusion. This, in turn, would increase the rate of pumping.

From Fig. 4, one predicts a telling signature of LWI/EIT to be extremely narrow-band emission observed at both the H(α) and Ly-β line centers. The HRS pumping process should be manifest by symmetrical absorption of continuum light around Ly-β in a pattern that might superficially resemble the one shown in Fig. 3 (In Fig. 3, however, the apparent absorption dip has a stellar origin, as was noted above.)

An LWI/EIT mechanism can reasonably explain certain other intense, extremely narrow emission lines recorded by astronomers, examples being the sodium D-line doublet appearing in HD 44179, or the powerful O VI (1032 Å, 1037 Å) emission doublet that dominates the FUV spectra of symbiotic stars such as RR Tel. In both these cases, LWI/EIT would have to occur via the so-called ‘V’ scheme, which incidentally is the easiest one to excite in the presence of significant thermal Doppler broadening (Boon et al. 1999). However, the environments existing in cold, collisionless neutral clouds surrounding H II regions are generally favorable for all LWI/EIT schemes.

M.O. Scully has coined the word phaseonium to describe an ensemble of coherently phased atoms. An LWI based upon such a medium, he suggests, might appropriately be termed a phaser. Should the occurrence of LWI/EIT in space ever become substantiated, widespread usage of these terms in astronomy might follow.

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