*The Diffuse Interstellar Bands*
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# $H_2$ as a Possible Carrier of the DIBs?

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**Abstract.** In the 1990s the hydrogen molecule, by far the most abundant molecular species in the interstellar medium, has been proposed as a possible carrier of the diffuse interstellar bands. While some remarkable coincidences were found in the rich spectrum of inter-Rydberg transitions of this molecule with DIB-features, both in frequency position as in linewidth, some open issues remained on a required non-linear optical pumping scheme that should explain the population of certain intermediate levels and act as a selection mechanism. Recently a similar scheme has been proposed relating the occurrence of the UV-bump (the ubiquitous 2170 Å extinction feature) to the spectrum of $H_2$, therewith reviving the $H_2$ hypothesis.

**Keywords.** ISM: molecules, extinction, $H_2$, radiation mechanisms: nonthermal.

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The identification of the carrier(s) of the diffuse interstellar bands (DIBs) is an enigma which has been around for almost a century now. The almost randomly occurring absorption features of varying widths and strengths throughout the entire visible spectrum appear persistently and reproducible in the direction of reddened stars. Consensus seems to have emerged on the carriers of the DIBs being gas-phase poly-atomic molecules, most likely with a carbon-based frame. However, spectra of rotational manifolds will give rise to band envelopes exhibiting a strongly temperature dependent width. The DIBs in the visible domain do not display such feature of varying width, with the exception of the DIB-like features observed in emission in the red rectangle by Sarre *et al.* (1995) and the recently observed anomalous profiles of infrared DIBs in Herschel 36 by Dahlstrom *et al.* (2013). In these two examples the varying widths are ascribed to temperature effects.

In the 1990s Sorokin & Glownia (1995) formulated a hypothesis assigning as carrier of DIBS the inter-Rydberg transitions in the $H_2$ molecule as part of a two-photon pump scheme involving Lyman-$\alpha$ radiation. An hypothesis involving molecular hydrogen is attractive since the density of $H_2$ is estimated to be higher by $10^6 - 10^9$ times than that of other proposed carriers. The proposed scheme, involving intermediate $C^1\Pi_u, v = 9$ levels in $H_2$ as the ground levels for the DIB-absorptions, was shown to not yield exact matches with DIBs in a two-photon laser experiment carried out by Hinnen & Ubachs (1996a). However, strikingly, the spectral features observed when scanning the second laser wavelength in the visible domain appeared as DIB-like profiles: resonances of varying widths and shapes. Further investigations exploring a much wider wavelength range uncovered many resonances in the inter-Rydberg spectrum of $H_2$, some of which coincident with DIBs, but many strong resonances not coinciding with DIBs (Hinnen & Ubachs 1996b). The laboratory investigations finally led to a remarkable result shown in Fig. 1. When using the $C^1\Pi_u, v = 6$ state as an intermediate, for three different rotational and $\Lambda$-doublet levels, in each case a single isolated resonance was found, while tuning over a wide wavelength interval. All three resonances were found to coincide, within spectroscopic error margins, with DIBs (Ubachs *et al.* 1997). In addition the widths of the three resonances also matched the widths of the corresponding DIBs. It is noted

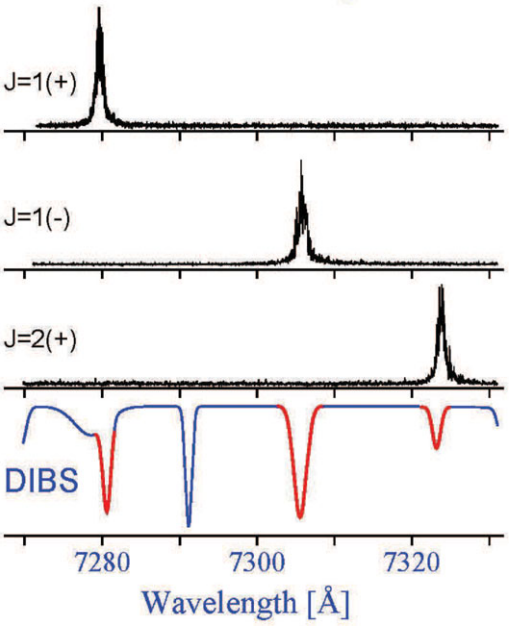


**Figure 1.** Observed double-resonance spectra of $H_2$ using the $C^1\Pi_u, v = 6$ state as an intermediate for the three levels with quantum levels indicated. Here J denotes the total angular momentum and (+) the overall parity of the state, which is different for each of the Λ-doublet states in a Π state. The figure shows a coincidence within a fraction of the linewidth with a DIB displayed in the lower spectrum. Figure adapted from Ubachs *et al.* (1997).

further that the three intermediate levels are excited by R(0), R(1) and Q(1) transitions in the C-X(6,0) band, so connecting all possible transitions from J=0 and J=1 levels, the ground state levels of para- and ortho hydrogen in the $X^1\Sigma_g^+$ state. It is only these two ground state levels that are abundantly populated at low temperatures. All these issues combined make the observation as shown in Fig. 1 truly remarkable.

These experimental investigations gave the insight that the widths of DIBs could in principle derive from autoionization. Autoionization gives rise to a homogeneous broadening effect, which is temperature independent. Moreover, as is known from Fano's theory of autoionization, asymmetric profiles can similarly occur, and are well understood from interactions between discrete resonances and the continuum.

It is noted that the two-photon laser excitation studies clearly showed that in the $H_2$ inter-Rydberg spectrum many resonances exist that do not coincide with DIBs. This may be considered as a show-stopper for the $H_2$-hypothesis. It may be concluded that for the $H_2$ hypothesis to remain valid selection mechanisms must be active that favor some intermediate states as DIB-carrying ground states. Already in the first publication on the $H_2$ hypothesis, Sorokin & Glownia (1995) identified the presence of strong Lyman-$\alpha$ radiation as a selection mechanism, in the particular case to select $C^1\Pi_u, v = 9$. In later publications other pumping and selection mechanism were invoked (Sorokin & Glownia 1997, Sorokin *et al.* 1998) ranging from stimulated Raman pumping to four-wave mixing and electromagnetically induced transparency, all phenomena well-known in non-linear optics. In some schemes also assignments of some of the unidentified infrared emission bands in the range 3-20 $\mu$m to inter-Rydberg $H_2$ transitions were provided. The proposed non-linear-optical radiative transfer models were criticised for the fact that the ultraviolet

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radiation fields prevailing in the interstellar medium should be insufficiently intense to produce the non-linear optical effects described (Snow 1995).

In much later years the concept of $H_2$ molecules involved in non-linear optical processes in the interstellar medium was reiterated in a different context. The broad extinction feature near 2170 Å, known as the UV-bump, was also assigned in terms of a two-photon scheme in molecular hydrogen (Sorokin & Glownia 2005). Very recently evidence from FUSE satellite VUV spectra of OB stars was added in support of this scheme (Sorokin 2013). This intriguing proposal revives the $H_2$ hypothesis as such. In order to settle the combined issues of the $H_2$ hypothesis, *quantitative* radiative transfer models should be developed, including realistic ultraviolet radiation fields for the interstellar and circumstellar medium, and invoking all the coherences that could give rise to stimulated and non-linear optical effects. Such models have never been explored.

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