The Mysteries of 6565 Å Absorption Feature of the Galactic Halo

Shiv K. Sethi1, Yuri Shchekinov1,2, and Biman B. Nath1
1 Raman Research Institute, Sadashivnagar, Bangalore 560080, India
2 Lebedev Physical Institute, 53 Leninsky Avenue, Moscow, 119991, Russia

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Abstract

We consider various possible scenarios to explain the recent observation of what has been called a broad Hα absorption in our Galactic halo, with peak optical depth \( \tau \approx 0.01 \) and equivalent width \( W \approx 0.17 \) Å. We show that the absorbed feature cannot arise from the circumgalactic and ISM Hα absorption. As the observed absorption feature is quite broad (\( \Delta \lambda \approx 30 \) Å), we also consider CNO lines that lie close to Hα as possible alternatives to explain the feature. We show that such lines could also not account for the observed feature. Instead, we suggest that it could arise from diffuse interstellar bands (DIBs) carriers or polyaromatic hydrocarbons (PAHs) absorption. While we identify several such lines close to the Hα transition, we are unable to determine the molecule responsible for the observed feature, partly because of selection effects that prevent us from identifying DIBs/PAHs features close to Hα using local observations. Deep integration of a few extragalactic sources with high spectral resolution might allow us to distinguish between different possible explanations.

Key words: diffuse radiation – intergalactic medium – ISM: abundances – ISM: general – ISM: molecules – quasars: general

1. Introduction

A recent observation of possible Hα absorption along the lines of sight to Sloan Digital Sky Survey (SDSS) galaxies has put the physical state of hydrogen atoms in the Galactic halo in a spotlight. Zhang & Zaritsky (2017; hereafter ZZ17) stacked the spectra of more than 700,000 galaxies from SDSS. Focusing on the wavelength range of 6340–6790 Å, they detected a broad Hα absorption line with peak optical depth \( \tau \approx 0.01 \) and equivalent width \( \sim 0.17 \) Å. The correlation between the features and Galactic longitude is consistent with the absorbing systems being located at rest in our Galactic halo within \( L \sim 100 \) kpc.

The measured width of the line corresponds to a line of sight velocity dispersion of order \( \pm 700 \) km s\(^{-1}\), but there is significant uncertainty in this interpretation, and the velocity spread can be of order \( \pm 390 \) km s\(^{-1}\) (ZZ17). The absorption line is consistent with an average column density of hydrogen atoms in \( n = 2 \) state: \( N_2 \approx (7.34 \pm 0.04) \times 10^{21} \) cm\(^{-2}\). The mean absorption map suggests that the absorption is isotropic and is prevalent across most lines of sight.

In the next section, we discuss possible implications of interpreting the observed feature as Hα absorption; we discuss direct constraints and possible mechanisms to populate the \( 2p \) and \( 2s \) states. In Section 3, we consider physical processes that might explain the observation while obviating the direct constraints. We consider trapped Lyα lines, metal lines, and complex molecules (diffuse interstellar band (DIB) carriers and polyaromatic hydrocarbon (PAH)) as possible candidates.

2. Maintaining Hα-absorbing Circumgalactic Gas

The crux of the problem is maintaining a large amount of Hα-absorbing gas in the halo, which can explain the observed value of column density \( N_2 \). There are two aspects to consider in order to understand this observation: pumping \( \text{H}(n = 2) \) states to explain the observed column density, and constraining emission from the excited states.

The observed absorption could be caused by either the \( 2p \) or \( 2s \) state. The Hα transition could arise from multiple transitions: two transitions originating from the \( 2p \) level, \( 2p–3d \) and \( 2p–3s \), or by a \( 2s–3p \) transition.\(^8\) ZZ17 reported an absorption trough with peak optical depth \( \tau \approx 0.01 \) and equivalent width \( W = 0.170 \pm 0.001 \) Å, yielding a column density \( N_2 = 1.13 \times 10^{20} W / (f \lambda^2) \) Å cm\(^{-2}\) with an oscillator strength \( f = 0.6410 \). In principle, we could derive multiple column densities depending on the oscillator strengths of these transitions, but that does not change the conclusions we reach in the paper.

One can readily rule out the \( 2p \) level if the absorption originates in a medium optically thin to Lyα photons. The corresponding Lyα photon energy density in the halo due to radiative de-excitation of the \( 2p \) level would be \( N_2 A_{2p, 1s} (10.2 \text{ eV}) / c \approx 10^{43} \text{ eV cm}^{-3} \), which is more than a factor \( \approx 10^5 \) larger than the observed value of UV background in the solar neighborhood (see, e.g., chapter 12 in Draine 2011). Therefore, we consider the \( 2s \) state. The decay of the \( 2s \) state gives two photons with a broad energy distribution (Spitzer & Greenstein 1951). As the A-coefficient of this decay is nearly eight orders of magnitude smaller than Lyα transition, it causes a corresponding decrease in the photon energy density. Even this decay gives a photon number density that is larger than the observed value by a factor \( 10^4 \), but we consider it as a plausible mechanism to underline the possible physical processes that can populate the first excited state of hydrogen in the interstellar medium (ISM).

2.1. 2s State

As the \( 2s \) state is metastable with a two-photon decay rate \( A_{2s, 1s} = 8.227 \) s\(^{-1}\) (Spitzer & Greenstein 1951), keeping the excited state sufficiently populated is much easier in this case than compared to the \( 2p \) state. There are several mechanisms

\(^8\) https://physics.nist.gov/PhysRefData/Handbook/Tables/hydrogentable3.htm
for populating the 2s state: radiative recombination of ionized hydrogen to the 2s state, collisional excitations by thermal electrons (contributions from protons and other ions is negligible), and radiative excitations of higher-energy levels $n \geq 3$ by Lyman-series photons followed by radiative decays to the 2s state.

The equation of the balance of the 2s level is given by

$$n_{2s} = \frac{\alpha_2(T) n_e^2}{A_{2s,1s}} + \frac{C_{1s,2s}(T) n_{1s}}{A_{2s,1s}} n_{1s},$$

(1)

where $C_{1s,2s}(T), \alpha_2(T)$ is the coefficient of collisional excitation (e.g., Fritsch & Lin 1982; Janev et al. 1987; McLaughlin et al. 1997) and the recombination to the 2s state, respectively. $\Gamma_{1s,2s}$ is the rate at which Lyman-series photons can populate the 2s state; $\Gamma_{1s,2s} = \sum_{i>2} \Gamma_{i,2s}$. Here $\Gamma_{1s,2s}$ gives the rate at which absorbed photons populate states with $i = n > 2$, and $P_{2s}$ is the probability that through radiative decay the atom returns to the 2s state, e.g., $P_{32} = A_{32}/(A_{31} + A_{32})$. The absorption of photons by the 3p state dominates this process.

2.1.1. Recombination

This process will dominate if the medium is highly ionized or $n_e \approx n_{H^0}$, where $n_{H^0}$ is the total hydrogen density. Assuming a photoionized region with $T = 10^4$ K, this gives

$$n_{2s} \approx \frac{\alpha_2(T) n_e^2}{A_{2s,1s}} \approx 10^{-12} \left( \frac{n_e}{10 \text{ cm}^{-3}} \right)^2 \text{ cm}^{-3},$$

(2)

To satisfy the observation, $n_{2s} \approx n_e / L$, we require the size of the region $L \approx 100$ kpc for $n_e \approx 10$ cm$^{-3}$. This results in an emission measure (EM)

$$\text{EM} \approx A_{2s,1s} n_e^2 / \alpha_2(T) \approx 10^7 \text{ cm}^{-6} \text{ pc}.$$  

(3)

For comparison, the Orion nebula has an EM $\approx 5 \times 10^6$ cm$^{-6}$ pc. For the ionized gas of such an EM along every line of the sight through the halo, as the observation suggests, the free–free opacity exceeds unity for $\nu \leq 1$ GHz. This means that extragalactic sources would not be observable for radio frequencies below 1 GHz. Thus, we can rule out this physical process as being responsible for populating the 2s state. This inference cannot be changed by clumping the gas along the line of sight, as both $n_{2s}$ and free–free absorption depend upon the square of $n_e$.

2.1.2. Collisions

Collisional excitation can contribute to populating the 2s state in partially ionized gas at $T \approx 10^4$ K. This gives us

$$n_{2s} \approx \frac{C_{1s,2s}(T) n_{1s}}{A_{2s,1s}} \approx 4 \times 10^{-15} \left( \frac{n_{H^0}}{10 \text{ cm}^{-3}} \right)^2 \text{ cm}^{-3}.$$  

(4)

For computing the electron density we assume that the medium is collisionally ionized for $T \approx 10^4$ K. Using $L \approx N_e / n_{3s}$, we get the size of the absorbing column, $L \approx 50$ Mpc for $n_{H^0} \approx 10$ cm$^{-3}$. Clearly, this case results in even more unrealistic values of densities and the absorbing column. We have checked the whole range of $T$ and $n_{H^0}$, and could not come up with a single case that gives reasonable values such as $n_{H^0} \lesssim 1$ cm$^{-3}$, as observed in the local ISM and in the halo within $L \lesssim 100$ kpc.

2.1.3. Lyman-series Photons

If the possible H$\alpha$ absorption originates in an extended Galactic halo and/or in the surrounding IGM gas of the Local group as suggested by (ZZ17), one can assume that absorbing gas is exposed to the extragalactic UV with a photon flux at the Ly-continuum edge $F_{\nu}^{p} = 10^6$ J$\lambda$ phot cm$^{-2}$ s$^{-1}$ (see also more recent measurements at $\lambda \approx 2000$ Å in Franceschini & Rodighiero 2017). We further assume that photon flux at $\lambda \approx 1000$ Å is of the same order of magnitude $F_{1000} \approx F_{\nu}^{p}$. We use this value to compute $\Gamma_{1s,2s} \approx \sigma_{1s,3p}(T) n_e c (A_{32}/A_{31} + A_{32})$, where $\sigma_{1s,3p}$ is the cross-section of photon absorption from 1s to 3p level at the line center, and $n_e \approx n_e / c$ is the number density of photons that cause the transition. This gives us

$$n_{2s} = \frac{\Gamma_{1s,2s} n_{H^0}}{A_{2s,1s}} \approx 5 \times 10^{-9} \left( \frac{n_{H^0}}{10 \text{ cm}^{-3}} \right) \text{ cm}^{-3}.$$  

(5)

For our estimate, we use $T = 5000$ K, as expected for the warm neutral medium of the ISM, and use the absorption cross-section at the line center. In this case, we get $L \approx 400$ pc for $n_{H^0} \approx 1$ cm$^{-3}$. Clearly this case gives a more believable picture: a single region of a fraction of the size of the Galactic halo with hydrogen number density and UV flux expected in the ISM.

There are two related issues that need to be discussed before this estimate becomes reliable. First, the observed line width, which could be due to turbulent motion, is nearly 50 times larger than the thermal line width that we assumed here. If we had used the value of absorption line-center cross-section suitable for the observed line, then the corresponding numbers for $L$ or $n_{H^0}$ would be higher by a factor of 50.

3. Trapped Ly$\alpha$, Metal Contamination, DIB, and PAH

There are at least two possible ways to circumvent the constraints in this discussion. The first would be to assume that the 2p emission originates from a region that is optically thick to Ly$\alpha$, and the trapping of photons in the region reduces the effective decay time of the 2p, which also diminishes the luminosity in the line. The second approach would be to posit that the observed absorption is caused by a transition from the ground state of an element other than hydrogen, or that it arises from electronic transitions of more complex molecules (e.g., DIB carriers or PAH).

3.1. Ly$\alpha$ from Optically Thick Regions

If the Ly$\alpha$ emission emerges from a region optically thick to this photon, then the coupled problem of solving level populations along with the evolution of the radiative intensity can be greatly simplified under the condition of large line-center optical depth. In this case, the effective $A$-coefficient is replaced by $A_{2p,1s}/(0.5\tau)$, where $\tau$ is the optical depth at the line center (e.g., see Draine 2011, chapter 19; for a more recent

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4. Collisional excitation/recombination to states $n \geq 3$ followed by radiative decay to 2s state have negligible contribution.

5. In this case, each atom that makes a transition to the 2s state is accompanied by H$\alpha$ emission. However, this emission is isotropic and the flux of these photons along the line of sight is proportional to the solid angle of the observation (roughly the square of an arcsecond), which is negligible.
discussion, see Dijkstra et al. 2016). In this case, the occupancy of the 2p state increases by \( \tau \) and the luminosity in the Ly\( \alpha \) decreases by the same factor. To model this case, we need to ensure that the occupancy of 2p far exceeds the occupancy of the 2s state, and that the luminosity of the line satisfies the constraints on sky brightness. The former can be achieved by exciting the line with collisions, a case already discussed above. Any transition to states \( n > 2 \) yields a Ly\( \alpha \) photon after a few scatterings, and therefore the occupation of the 2s state is suppressed with respect to the 2p state that gets populated by Ly\( \alpha \) photons for which the number of scatterings is \( N_{\text{cat}} \approx \tau \). To achieve the latter, we need an optical depth \( \tau > 10^{10} \), which puts strong constraints on the H1 column. This gives us:

\[
L_{2p} \approx \frac{0.5C_{1s,2p}(T)n_{1s}n_{1s}(\alpha)}{A_{2p,1s}} \approx 1.3 \times 10^{-10} \left( \frac{\mu_{\text{H}}}{\text{10}^3} \right)^{3/2} \text{cm}^{-3}
\]

As \( n_{2p} \ll n_{1s}, n_{3s} \approx n_{1s} \) in this case. \( \tau \approx \sigma_{0}(0)n_{\mu}L \), where \( \sigma_{0}(0) \) is the cross-section for Ly\( \alpha \) at the line center; we assume \( T = 10^{4} \text{ K} \). However, \( L \approx n_{2p}/n_{2p} \) to satisfy the observation of H\( \alpha \) absorption, which gives:

\[
n_{2p} \approx \left( \frac{0.5C_{1s,2s}(T)n_{1s}n_{1s}(\alpha)}{A_{2p,1s}} \right)^{1/2}
\]

For \( n_{\mu} = 10^2 \text{ cm}^{-3} \), the size of the region, \( L \approx 1.7 \text{ kpc} \) and \( \tau \approx 5 \times 10^{10} \), and H1 column density, \( N_{\text{H1}} \approx 5.2 \times 10^{23} \text{ cm}^{-2} \). These numbers are clearly unrealistic. A change in hydrogen density does not alleviate this problem. Also, the observed velocity width decreases the line-center cross-section by a factor of 50, which makes the scenario delineated here even less plausible.

### 3.2. Metal Lines

Given that the width of the reported line is close to 30 Å, it is worthwhile to investigate whether this line could arise from metal lines that lie close to the H\( \alpha \) transition. We consider carbon, nitrogen, and oxygen as they are the most abundant elements in the ISM following hydrogen and helium. We neglect the lines arising from transitions between two excited states of the atom to avoid facing the same issues we discussed in Section 2, e.g., C\( \text{II} \) line at \( \lambda \approx 6578 \text{ Å} \) which causes a transition between two excited states.

Two lines of singly ionized nitrogen (N\( \text{II} \))—3P\( 1 \rightarrow 1D_{2} \) (6549.9 Å) and 3P\( 2 \rightarrow 1D_{2} \) (6585.3 Å)—lie close to H\( \alpha \) emission. One distinct advantage in this case is that the absorption is caused, unlike H\( \alpha \) absorption, by an element in its ground state, which means that there are no constraints from the decay of the line.

The abundance of nitrogen in the local ISM is \( 7 \times 10^{-5} \) (e.g., Draine 2011). For this, we conclude that all of the nitrogen is singly ionized. For \( T \approx 10^{4} \text{ K} \), the cross-section at the line center for these two transitions \( \sigma_{N_{\text{II}}} \approx 2 \times 10^{-22} \text{ cm}^{2} \),

6 The ratio of the occupancy of 2s to 2p states scales as \( A_{2s,1s}/(\alpha A_{2p,1s}) \), see e.g., Dijkstra et al. (2016).

7 For large optical depth, the level population of the 1s and 2p states can thermalize or \( n_{2p} = 3n_{1s}\exp(-\mu_{1s}/(kT)) \). The equivalent condition is \( n_{2p} = n_{2p,1s} \approx A_{2p,1s}^{0.5} \), and it is not reached for the range of parameters relevant to this Letter.

To achieve the observed optical depth \( \tau \approx 0.01 \), with an average \( n_{\alpha} \approx 10^{-2} \), we require the absorbing column to be \( L \approx 30 \text{ Mpc} \), which is far in the access of the halo size of the Milky Way. Therefore, this can be ruled out as a plausible mechanism to achieve the observed optical depth.

### 3.3. Diffuse Interstellar Bands

If the observed features in absorption around the H\( \alpha \) line cannot be modeled as either the transition of hydrogen or metal, then it is conceivable that they arise from more complex molecules. In this section we explore this possibility. There are a plethora of spectral DIB features. These are presumably caused by carbon chains, PAH, and hydrogenated carbons. However, their origin remains highly uncertain. The typical DIB spectral width FWHM \( \sim 0.5-3 \text{ Å} \) (Hobb et al. 2008) is larger than the Doppler width for interstellar gas (see Chapter 6 in Tielens 2010), and it might mimic the observed wide Doppler width of the 6565 Å feature.

An ongoing European Southern Observatory (ESO) survey seeks to detect and characterize DIB for \( \lambda \approx 305-1042 \text{ nm} \) with unprecedented spectral resolution and signal-to-noise ratio, along more than 100 sight lines (Cox et al. 2017). The first results of this survey show a range of spectral features in the wavelength band of interest to us (for results on DIB, see also Tielens 2010, 2014). It should be pointed out that most of the observational data for DIBs (and their templates) in the ISM are obtained from the observation of absorption toward nearby stars in the Galactic plane. Some of these lines of sight show strong H\( \alpha \) absorption features that arise from the stellar atmosphere of the target star, e.g., Figure B1 of Cox et al. (2017).

Lan et al. (2015) stacked SDSS stars, galaxies, and quasistellar objects (QSOs) in order to detect DIBs in the Milky Way. Their composite absorption spectra, based on 40,000 stellar spectra and obtained after subtracting stellar spectral energy distributions (SEDs), show a discernible absorption feature at H\( \alpha \) frequency, which they attribute to stellar absorption residual. Even though 95% of the stars they use have temperatures in the range 4500–7000 K, the spectra of which are not expected to show prominent H\( \alpha \) absorption, a small level of residual absorption might remain if the SED of the star is corrected for. We note that if the feature they observe (peak optical depth \( \tau \approx 0.002 \) and \( \Delta \lambda \approx 10 \text{ Å} \)) is attributed to absorption by the ISM, it might be compatible with the results of (ZZ17). It is because stars compiled by Lan et al. (2015) lie at typical distance of 2–3 kpc, while the lines of sight analyzed by (ZZ17) traverse the Galactic halo, which could be 50–100 kpc. However, the errors incurred in subtracting stellar SED might be large enough to remove this weak feature expected from ISM.

This discussion shows that there exists an observational selection bias against the detection of DIB close to H\( \alpha \) transition. This is supported by observations of emission lines in the Red Rectangle nebula corresponding to DIB absorption lines, from regions excluding the central star, particularly the strong lines at \( \approx 6560 \) and 6570 Å (Sarre 1991; Scarrott et al. 1992). Further analysis has shown the presence of two relatively strong features at \( \lambda = 6552.4 \text{ Å} \) and 6563.4 Å without contamination from the H\( \alpha \) line (van Winckel et al. 2002).

This selection effect is avoided in the observation of absorption from extragalactic sources, e.g., SDSS galaxies,
for which intrinsic Hα absorption from stellar atmospheres is redshifted, e.g., the work of (ZZ17) or for late-type stars without strong Hα absorption in their spectra. We should also consider laboratory measurements of the spectra of PAH and complex molecules.

3.4. PAH Lines Near $\lambda = 6565$ Å

From laboratory measurements of the spectra of complex molecules, we present, as an example, a tentative list of molecular compounds and the corresponding lines that are reasonably close (within 30–40 Å) to the 6565 Å and which can, in principle, mimic Hα absorption:

1. naphthalene (Np) cation C10H5+: a feature at $\lambda \approx 6520$ Å ($f = 10^{-4}$, $\Delta \nu = 100$ cm$^{-1} = 42$ Å), and a weaker feature at $\lambda \approx 6600$ Å (Table 3 and Figure 3(a) in Salama & Allamandola 1991), vibronic transition from the ground state $^2B_{1g}(D_2) - ^1X^2A^+_g(D_0)$;
2. a hydrogenated form H$_2$HC$_2$H$_6$: a feature at 6550 Å ($f \approx 0.03$ to $\approx 0.05$; see Figures 5(d), (e), (f) in Hammonds et al. 2009);
3. protonated pyrene 2H-Py+: a relatively strong feature at 6550 Å (theoretical oscillator strengths lie around $f \sim 0.03–0.05$; Figure 4 and Table 2 in Chin & Lin 2016); and
4. [FePAH]$^+$ complexes with a band at 6600 Å ($f \approx 0.002$; Table 3 and Figures 2, 3 in Lanza et al. 2015).

3.4.1. Optical Depth of DIB/PAH Absorbing Halo Gas

Let us assume, as a conservative estimate, that the oscillator strength of the line is $f_{6565} \approx 10^{-3}$, the abundance of the carrying compound $\chi_{6565} \approx 10^{-8}$ (see, e.g., Tielens 2010, p. 218), and the mass of the compound is $\mu_{6565}$. Then the line-center optical depth is

$$\tau_{6565} \approx 8 \times 10^{-4} f_{6565}^4 \frac{f}{T_{4}^{-1/2}} N_{20}$$  

Here $N_{20} \equiv N_{H_1}/(10^{20} \text{cm}^{-2})$.

Similar estimates of typical optical depth for a DIB compound gives

$$\tau_{\text{DIB}} = \frac{\sqrt{\pi} e^2 f}{mc^2 \Delta \nu} \chi_{\text{DIB}} N(H) \approx 0.08 \frac{f_{\text{DIB}}^4}{T_{4}^{-1/2}} N_{20},$$

where the abundance $\chi_{\text{DIB}} \approx 3 \times 10^{-10}/f$, with $f$ being the oscillator strength is assumed following Tielens (2014).

From Equations (8) and (9) we can readily obtain the observed optical depth $\approx 0.005–0.01$ for an acceptable range of parameters. These estimates are also consistent with constraints from FIR emission (e.g., Tielens 2010). The main reason this constitutes a plausible mechanism as compared to metals is that the absorption cross-section is larger for PAH/DIB as compared to forbidden lines that lie close the ground state for metals (e.g., N II).

4. Summary

In this Letter, we attempt to explain a recent observation that reports the detection of a broad absorption feature ($\Delta \lambda \approx 30$ Å) at $\lambda \approx 6565$ Å in the Galactic halo (ZZ17). Even though the feature corresponds to the Hα wavelength, we argue that it could not arise from such a transition.

First, the decay of the excited state through the spontaneous de-excitation of the (optically thin) 2p and 2s levels gives a sky brightness that is incompatible with UV observations. Second, we show that the observed absorption feature cannot be modeled using 2s transition for parameters expected of the Galactic halo. We investigate the possibility of Lyα photons trapped in an optically thick region. In this case, the sky brightness constraint can be overcome only for unrealistically large optical depths.

We next consider CNO metal lines close to H$\alpha$ transition. All of the transitions that connect two excited states can be ruled out (e.g., C II) for the same reason as listed above. A doublet of singly ionized nitrogen (N II) has transition frequencies within 20 Å of H$\alpha$ transition and the transitions connect the ground state with an excited state, thereby obviating the sky brightness constraint. However, even in this case, we fail to find parameters that are compatible with expected properties of ISM and Galactic halo.

Finally, we consider DIB and PAH in order to explain the observation. There are a number of transitions of such complex molecules in the frequency range of interest. We show that known models of DIB and PAH, based on optical and UV absorption of far-infrared/near-infrared emission, might explain the absorption features, even though we are not able to identify the molecule responsible for this line. This could partly be due to the fact that Hα absorption in the local stars used to identify these line could constitute a selection bias in this case.

Deep observation of a few bright extragalactic sources (for a range of Galactic longitudes) with high spectral resolution (SDSS spectral resolution $\lambda/\Delta \lambda \approx 1500–2500$ could have caused blending of lines) and signal-to-noise ratio might reveal the nature of this mysterious absorption feature.

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References

Chin, C. H., & Lin, S. H. 2016, PCCP, 18, 14569
Cox, N., Cami, J., Farhang, A., et al. 2017, A&A, 606, A76
Dijkstra, M., Sethi, S., & Loeb, A. 2016, ApJ, 820, 10
Draine, B. T. (Ed.) 2011, Physics of the Interstellar and Intergalactic Medium (Princeton, NJ: Princeton Univ. Press)
Franceschini, A., & Rodighiero, G. 2017, A&A, 603, A34
Fritsch, W., & Lin, C. D. 1982, PhRvA, 26, 762
Hammonds, M., Pathak, A., & Sarre, P. J. 2009, PCCP, 11, 4458
Hobbs, L. M., York, D. G., Snow, T. P., et al. 2008, ApJ, 680, 1256
Janev, R. K., Langer, W. D., Evans, K., Jr., & Post, D. E., Jr. 1987, in Elementary Processes in Hydrogen-Helium Plasmas (Berlin: Springer), 321
Lan, T.-W., Ménard, B., & Zhu, G. 2015, MNRAS, 452, 3629
Lanza, M., Simon, A., & Amor, M. B. 2015, JPhB, 30, 1043
Salama, F., & Allamandola, L. J. 1991, JCPPh, 94, 6964
Sarre, P. J. 1991, Nat, 351, 356
Scarrott, S. M., Watkin, S., Miles, J. R., & Sarre, P. J. 1992, MNRAS, 255, 11p
Spitzer, L., & Greenstein, J. L. 1951, ApJ, 114, 407
Tielens, A. G. G. M. (Ed.) 2010, The Physics and Chemistry of the Interstellar Medium (Cambridge: Cambridge Univ. Press)
Tielens, A. G. G. M. 2014, in IAU Symp. 297, The Diffuse Interstellar Bands, ed. J. Cami & N. L. J. Cox (Cambridge: Cambridge Univ. Press), 399
van Winckel, H., Cohen, M., & Gull, T. R. 2002, A&A, 390, 147
Zhang, H., & Zaritsky, D. 2017, NatAs, 1, 0103