On the relationship between the continuum of interstellar extinction curves, the 2200 Å bump, and the diffuse interstellar bands

Frederic Zagury

ABSTRACT

A previous article argued that the antagonism between sight-lines with and without a bump at 2200 Å disappears, and that the observed properties of interstellar extinction can be globally understood, if it is accepted that scattered starlight contaminates the observed spectrum of reddened stars. The present paper develops this new paradigm by providing a better understanding of the characteristics of this scattered light. It further examines the consequences of this revision of interstellar extinction theory for interpreting the 2200 Å bump and the diffuse interstellar bands (DIBs). Two implications are worth noting: (1) the effect of interstellar extinction on cosmic distance estimations needs to be reconsidered; (2) it is unnecessary to invoke hypothetical particles, such as Poly Aromatic Hydrogenated molecules (PAHs), to explain the peculiarities of interstellar extinction. Hydrogen, by far the most abundant constituent of interstellar clouds, should alone account for the three major features of interstellar extinction: the departure of the continuum from linearity, the bump, and the DIBs.

Subject headings: ISM: lines and bands; planetary nebulae: general — Physical Data and Processes: astrochemistry — Physical Data and Processes: radiative transfer — Physical Data and Processes: scattering — ISM: dust, extinction — ISM: lines and bands

1. Introduction

After decades of research and despite a now well-established set of observations, studies on interstellar extinction still lack a firm and internally-consistent theoretical framework. The nature of the particles that would explain the 2200 Å bump and the far-ultraviolet rise of extinction curves remains controversial. In the visible wavelength range, the carrier(s) of the diffuse interstellar bands (DIBs) have still not been identified.

It is taken for granted in interstellar extinction studies that an observer sees the direct light from reddened stars dimmed by different types of interstellar particles in the line of sight. However, this assumption leads to contradictions between theory and observations at ultraviolet wavelengths [Zagury (2013), Sects. 5 to 7 this paper].

An alternative, the only one in fact, would be to accept that a large amount of scattered starlight is mixed with the direct light we receive from reddened stars [Zagury 2013]. This shift in perspective would unify existing observations in a consistent picture. It would simplify the true extinction law of interstellar dust (which is linear over the whole spectrum, $\tau_\lambda \propto 1/\lambda^p$, $p \sim 1$), and explain the observed relationship between the extinctions in the optical and in the ultraviolet parts of the spectrum. It would also explain why some extinction curves have no 2200 Å bump and continue to be linear in the ultraviolet spectrum (Fig. 1). Finally, it would settle long-lasting controversies on the value of the ratio of total to selective extinction $R_V$ parameter (Sect. 10).

This alternative is itself not free from difficulties. If light received from a reddened star decomposes into direct and scattered light components, the latter can overwhelm the former. At ultraviolet wavelengths a star would appear much brighter if it could be observed through an interstellar cloud of pure gas (no dust) than would be the case without the cloud in the line of sight. The
cloud (with no dust) would amplify the signal from the background star and act more like a lens than as an extinction medium. On observed extinction curves this effect is masked by the exponential extinction $e^{-\tau_\lambda}$ ($\tau_\lambda \propto 1/\lambda^p$, $p \sim 1$) that interstellar dust introduces. It is recovered when the latter is removed (Fig. 2).

Diffraction in the forward direction, the specificity of which is well known and recognized [Van de Hulst 1981, Hecht 2003], should alone account for the strength of the scattering component in the spectrum of reddened stars. However, no theory provides a straightforward fit to interstellar extinction curves. Textbooks [Hecht 2003, Stone 1963] discuss and illustrate the pattern of forward diffracted light by randomly distributed particles, but their accounts remain at a qualitative level. The formula for the irradiance of the forward scattering by a slab of identical particles, derived by H.C. van de Hulst in the 1950s, seems to anticipate the lensing effect of interstellar clouds, but it predicts ratios of the scattered to the direct starlight intensities that are much too high, and also a different wavelength dependence than is actually observed [Zagury & Pellat-Finet 2012 and Sect. 11.1].

A particularity of forward scattering in the case of interstellar extinction is the impressive size, a few thousand kilometers wide, that Fresnel zones can reach on astronomical scales. The larger the Fresnel zone is at the position of the cloud, the greater the power available for scattering and the greater the proportion of scattered starlight in the spectrum of a reddened star.

It is the combination of complete forward scattering, large Fresnel zones, and identical particles (atomic and/or molecular hydrogen) that explains the very large proportion of scattered starlight in the spectrum of reddened stars and why observed extinction curves depart from linearity in the ultraviolet spectrum. Thus restated, the issue raised by ultraviolet extinction curves highlights the necessity of shifting research on interstellar extinction from an inquiry into the chemistry of the interstellar medium to a problem of optics.

This shift would reframe our understanding of the two major issues cited above, the 2200 Å bump and the DIBs. The bump, a singular figure in the ultraviolet part of extinction curves, must be seen as an interruption of the scattered light component of the spectrum of reddened stars (Sect. 13 and Fig. 1).

In 2005 the state of DIB research was summarized as follows:

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, 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 ... 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![1] ... [Considering] that 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-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. (Sorokin & Glownia 2005).

As the sensitivity and the spectral resolution of

---

1 Similar assessment are found in Tielens 2008; Draine 2009.
observations increase, new DIBs (now over 500, see Hobbs et al. (2009)) continue to be found, but, over ten years after the Sorokin & Glownia (2005) paper and twenty years after the Boulder meeting, the identification of the "large, complex molecules" that would explain the features is at a standstill. Neither fullerenes (Campbell et al. 2015), nor Poly Aromatic Hydrogenated molecules (PAHs), will account for the full DIB spectrum, and the presence of these molecules in interstellar clouds raises difficulties on account of their supply exceed in Sect. 14.2 and Ubachs (2014). The situation is all the more perplexing because the extinction theory for distance estimates and for ongoing research on hypothetical particles of the interstellar medium, such as the PAHs, are drawn in Sect. 14.

An appendix summarizes elementary principles and particularly useful results of diffraction theory. The small vibrations of the hypothetical "particles éclairantes" (or "molécules étherées" (Fresnel 1866, p. 202, 375)) that Fresnel imagined to account for the propagation of light, which still inform modern presentations of classical diffraction theory (Peyman et al. 1964, Born 1999, Hecht 2003), should find an even more realistic application in coherent Rayleigh scattering than they do for the free propagation of light.

2. Interstellar extinction curves

Extinction curves $A_{\lambda}$ have been introduced as the magnitude of the ratio $F/F_{ref}$ of the spectrum $F$ of a reddened star to the spectrum $F_{ref}$ of a non-reddened star of the same spectral type: $A_{\lambda} = -2.5 \log(F/F_{ref}) + C$. Constant $C$ is eliminated by referring the extinction to a given wavelength (Zagury 2012). Extinction curves are usually normalized by the reddening $E(B-V) = A_B - A_V$ of the star. The reddening $E(B-V)$ is a measure of the column density of interstellar matter between the star and the observer. Normalized extinction curves measure the extinction per unit reddening in the direction of the star.

In a pure extinction process $A_{\lambda}$ is nearly the wavelength-dependent optical depth $\tau_{\lambda}$ in the expression $F/F_0 = e^{-\tau_{\lambda}}$ of the attenuation of light traversing a medium. It is a convenient parameter to characterize the particles along the line of sight and their column density. If different particles or media are along the line of sight, $F/F_0$ is the product of the $e^{-\tau_{\lambda}}$ over the particles and media, and the extinction curve is the sum of the extinctions $A_{\lambda}$.

These properties justify the longstanding choice of $A_{\lambda}$ over $F/F_{ref}$ (given by observation) as the variable for interstellar extinction observations. This choice, however, impacts the representation of extinction curves and affects how they are in-
terpreted. The replacement of $F/F_{ref}$ by $A_\lambda$ can be particularly misleading if the pure extinction of starlight is not the only process at work.

Both understandings ($\propto F/F_{ref}$ or $-2.5 \log (F/F_{ref}) + C$) can be used to designate an extinction curve since the context generally prevents confusion. A 'linear' (or quasi-linear) extinction law means that the wavelength dependence of the extinction is $\tau_\lambda \propto 1/\lambda^p$ and equally that the attenuation of light is $F/F_{ref} \propto e^{-a/\lambda^p}$ ($p \approx 1$). Constant $a$ can be related simply to the reddening $E(B-V)$ for any value of the ratio of total to selective extinction $R_V = A_V/E(B-V) = \tau_V/(\tau_B - \tau_V)$ (Zagury & Turner 2012).

3. Observed properties of interstellar extinction curves

Within 1 to 0.4 $\mu$m in the visible wavelength range, all extinction curves follow a linear extinction law $\tau_\lambda \propto 1/\lambda^p$, $p \approx 1$ ($F/F_{ref} \propto e^{-a/\lambda^p}$). The linearity of the extinction tends to break under 400 nm, as if there was less extinction than predicted by the continuation of the linear law into the near-ultraviolet domain (Nandy 1964; Zagury 2012).

In the ultraviolet most extinction curves exhibit a singular broad absorption-like band centered close to 217.5 nm, the 2200 Å bump (bottom plot of Fig. 1). Curves with a bump have been most studied but, as Fig. 1 clearly demonstrates, extinction curves are not all bump-like. Some extinction curves do not have a bump, and when this is so the curves are always linear down to the bump region (middle plot of Fig. 1). In some cases the curves continue to be linear over the entire ultraviolet spectrum (top plot of Fig. 1).

Observation thus separates three classes of extinction curves: bump-like; linear down to the near-ultraviolet (the bump region); and linear over the whole visible-ultraviolet wavelength range (Fig. 1). The International Ultra-violet European (IUE) telescope has observed hundreds of reddened stars: with no exception, all extinction curves, whether they are observed in the Galaxy or in the Magellanic Clouds (Zagury 2007), fall into one of these three categories.

Extinction curves that are linear in the ultraviolet deserve special attention. They are more frequently observed in the Magellanic Clouds but are also present in the Galaxy. Other than that there is no fundamental difference between Magellanic and Galactic extinction curves (Zagury 2007).

In the Galaxy linear extinction curves are observed in two circumstances only: when the reddening is very low and when the obscuring interstellar matter is close to the star (for instance planetary nebulae) (Sitko et al. 1981; Seab et al. 1981; Zagury 2005, 2013). At extremely low reddening (e.g. less than 0.08 mag.) extinction curves are always linear over the whole visible-ultraviolet wavelength range (Zagury 2001b).

It is clear from Fig. 1 that extinction curves with a bump and linear extinction curves anticorrelate: the bump disappears when and only when the linearity of the extinction curve in the visible spectrum extends to the near-ultraviolet wavelengths or farther. Fig. 1 also shows that reddening is very low and when the obscuring interstellar matter is close to the star (for instance planetary nebulae) (Sitko et al. 1981; Seab et al. 1981; Zagury 2005, 2013). At extremely low reddening (e.g. less than 0.08 mag.) extinction curves are always linear over the whole visible-ultraviolet wavelength range (Zagury 2001b).

4. Interstellar extinction curves in the standard framework

Interstellar extinction curves have been analyzed under the assumption that the light we receive from the direction of a reddened star is the direct light from the star, extinguished by interstellar particles along the line of sight.

Under this assumption three types of particles, each having its own extinction law, are both necessary and sufficient to account for the variations of the extinction curve with the direction of observation (Greenberg 2000). The linear extinction law in the visible part of the spectrum was justified early on by a size distribution of interstellar grains (Greenstein 1958). The bump and the far-ultraviolet region are supposed to result from the extinction of light caused by two different species of molecules that still await a formal identification.

Greenberg & Chlewicki (1983) found that the far-ultraviolet rise of extinction curves does not correlate with either the visual extinction or the 2200 Å bump. Several articles (for instance Meyer & Savage (1981); Massa & Fitzpatrick (1986)) have shown that the bump is only partially, and
Fig. 1.— The three types of observed interstellar extinction curves: traditional bump-like extinction curves (bottom plot), extinction curves that deviate from linearity in the far-ultraviolet spectrum only (after the bump region, middle plot), linear over the whole visible/ultraviolet spectrum extinction curves (top plot). Each spectrum is the ratio of the spectrum of a reddened star to the spectrum of a reference star of low reddening and of the same spectral type. The spectra were normalized using the reddening difference $\Delta(B-V)$ between reddened and reference stars, and the Turner & al. (2014) extinction law for interstellar dust. Any extinction curve, in the Galaxy or in the Magellanic Clouds, falls into one of the three categories. It is clear from the figure that (i) $E(B-V)$ alone is not enough to fix the shape of an extinction curve, (ii) extinction curves with a 2200 Å bump and linear extinction curves anticorrelate.
not univocally, related to the visual extinction.

No connection to the environment has ever been established that would explain the variations of the extinction in the three spectral domains. Linear extinction laws exist in nature (atmospheric aerosols), but no laboratory experiment has yet reproduced bump-like extinction curves.

The random variation in the relative abundance of the three types of particles required by standard extinction models was further supported by the mathematical analysis of Fitzpatrick & Massa (1988): if three separate extinction laws (one for the visual extinction, one for the bump, and one for the far-ultraviolet rise) rule interstellar extinction, interstellar extinction curves must depend on a minimum of six independent parameters in addition to \( E(B - V) \).

5. The CCM paper and its one parameter fit

In contrast to the ideas that prevailed earlier (Sect. 4), Cardelli, Clayton, & Mathis (1989) (CCM hereafter) reached the remarkable conclusion that the variations observed in normalized extinction curves correlate over the whole spectrum. Another study, based on a larger sample of stars, reached the same conclusion a few years later (Bondar et al. 2006). CCM deduced that all normalized extinction curves with a bump can be approximated by a common fit that depends upon a single parameter, assumed to be \( R_V \). The CCM fit is purely mathematical and empirical.

The CCM paper, a breakthrough in the study of interstellar extinction, also gave rise to several difficulties. The most obvious one is that it remains embedded in the conventional view that extinction curves depend on different types of particles, which, as seen above, requires six (instead of one) independent parameters in addition to \( E(B - V) \).

A second difficulty arising from the CCM paper is the assumption that \( R_V \) is the free parameter of interstellar extinction. However, a simple derivation from the fit proves that, in the CCM framework, \( R_V \) must be a constant (\( = 1.46 \), Zagury 2012). \( R_V \) cannot be both variable, as supposed by CCM, and constant, as implied by the fit. This antinomy reflects the empirical nature of the CCM fit and the impossibility for \( R_V \) to be the free parameter of interstellar extinction. If interstellar extinction depends upon a single parameter (in addition to \( E(B - V) \)) and if \( R_V \) is not related to this parameter, \( R_V \) must stay constant (independent of direction, Zagury 2012).

The CCM fit is also not always accurate (fig. 4 in CCM), especially in the 2200 Å bump region, because the fit establishes a one-to-one correspondence between the bump and reddening (no bump means \( E(B - V) = 0 \) and no extinction, and vice versa). The fit thus samples one category of extinction curves only, the curves with a bump (bottom plot of Fig. 1). It ignores the linear and linear-down-to-the-bump-region extinction curves of Fig. 1 and is in manifest contradiction to the fact, already known in 1989, that the size of the bump is tied to \( E(B - V) \) but does not depend exclusively on it (Savage 1975; Meyer & Savage 1981).

An improved, still one-parameter-dependent fit, advantageously replaces the CCM parametrization for bump-like and linear-over-the-whole-spectrum (visible to far-ultraviolet) extinction curves (Zagury 2007). The fit shows that most extinction curves can be separated into a linear and a bump-like component. This separation breaks the univocal dependence of the bump on \( E(B - V) \) of the CCM fit, does not increase the number of free parameters, and proves that the normalization of extinction curves, as currently done in most studies, is not a straightforward process and is another reason for the inaccuracy of the CCM fit. Like the CCM fit, the new fit lacks a physical basis. However, it matches all observations with much greater precision, and it applies to nearly all extinction curves except for the minority of intermediate ones (middle plot of Fig. 1).

6. The incompatibility between the CCM and Fitzpatrick & Massa perspectives

The CCM and the Fitzpatrick & Massa fits proceed from two very different approaches. The latter relies on an assumption about interstellar extinction, the former on an empirical analysis of observations. The conclusions they reach are opposite and incompatible.

Assuming that interstellar extinction is the superposition of three different extinctions, Fitzpatrick & Massa conclude that reddening and six
independent (unrelated) parameters are necessary to account for the variety of observed extinction curves. In contrast, CCM and Bondar et al. (2006) consider extinction curves as a set of mathematical functions and search for the minimal dependencies of the curves. The CCM conclusion is unequivocal:

The most important result presented here is that the entire mean extinction law, from the near-IR through the optical and IUE-accessible ultraviolet, can be well represented by a single parameter. We have chosen to use $R_V$ for convenience, but it has no particular physical significance. No doubt other well-observed quantities similarly defined could have served in its stead.

... the deviations of the observations from the mean relation are impressively small ... in the real ISM the processes which modify the extinction at one wavelength also seem to modify the entire mean [normalized] extinction law in a regular way.

Few sight lines (7% out of 417 in Valencic et al. (2004)) escape the CCM relationship, the exceptions being most certainly related to its purely empirical nature. No doubt other well-observed quantities similarly defined could have served in its stead.

A recent textbook (Draine 2011) attempts to reconcile the opposing views of CCM and Fitzpatrick & Massa. The author suggests that CCM began with a seven parameter fit $F_{CCM}$ and ultimately transformed it into a one parameter $F_{CCM}$ fit, once each of the parameters had been expressed as a function of $R_V$.

The Draine (2011) account of the CCM article is confusing and inexact. There is no mention whatsoever in CCM of a seven (independent) parameter fit of extinction curves. No expression of the Fitzpatrick & Massa parameters as a function of the CCM parameter was ever found by CCM or anyone else. Such a finding would imply a dependency among the Fitzpatrick & Massa parameters that does not exist: the Fitzpatrick & Massa parameters have no relation one to another, and no relation to the free parameter of CCM. Moreover, the $R_V$ parameter, which CCM adopt as the free parameter of interstellar extinction, is usually taken to be constant in the Fitzpatrick & Massa fit. These differences only attest to the discrepancies between the Fitzpatrick & Massa and the CCM fits, and to the conflict between the assumptions underlying the Fitzpatrick & Massa thesis and observation, upon which the CCM finding relies.

Attempts to reproduce a large sample of extinction curves with physically meaningful particles, such as the PAHs, require a much larger number of free parameters than anticipated by observation, 226 (enough to sample the whole visible/ultraviolet spectrum) in a recent ApJ paper (Mulas et al. 2013). Although the authors concede that the number of free parameters must eventually be reduced from 226 to one, it can be doubted whether this goal is attainable.

7. Scattered starlight in the spectrum of reddened stars

The previous sections have shown that several logical deductions can be drawn from interstellar extinction observations. Interpretations of interstellar extinction curves based on the assumption that we observe the extinction of the direct light from stars will hardly comport with these conclusions. Standard three-components models for interstellar extinction face the following difficulties:

- a three-component model is incompatible with the dependency of extinction curves on reddening and on an additional parameter alone.
- the free parameter (in addition to $E(B-V)$) of interstellar extinction cannot be $R_V$, which must be a constant.
- the non-linearity of an extinction curve is intimately linked to the presence of the 2200 Å bump and vice versa. In other words, when (and only when) there is no bump, interstellar dust tends to recover a linear extinction law over the whole spectrum.
- the extinction cross-section of interstellar dust in nebulae does not have the near-ultraviolet break predicted by three-component models: the extinction law found in nebulae is continuous and linear over the
whole spectrum (Zagury 2000a, and next section).

In addition, the bump tends to disappear (and the extinction curve becomes linear) when there is very low reddening or when the star is close to the obscuring cloud.

Besides reddening, the only parameter that is seen to impact the shape of an extinction curve is the distance between the star and the interstellar matter obscuring it, a conclusion that does not make sense if extinction is the only process at work. This conclusion does make sense, however, if -and this is the sole alternative to standard explanations of interstellar extinction- what is observed is not only the direct light from the reddened stars, but also a non-negligible amount of scattered starlight.

8. What type of scattering?

Two types of scattering are commonly found in nature. One is scattering by particles with dimensions comparable to the wavelength. This type is observed to vary as $1/\lambda^p$, with $p$ of order 1, and is strongly forward oriented. Scattering by aerosols is the obvious example. The other case involves tiny particles, typically atoms or molecules, that are small compared to the wavelength. The scattering is then of Rayleigh type. It varies as $1/\lambda^4$ (a $1/\lambda^6$ term may also need to be considered (Dalgarno & Williams 1962)) and is nearly isotropic. Rayleigh extinction (and scattering) is far less efficient than dust extinction.

IUE ultraviolet observations of nebulae prove that light scattered by nebulae in near-forward directions behaves as $1/\lambda^p$ ($p \sim 1$) (Zagury 2000a). The scattering can safely be attributed to interstellar dust grains and suggests that their linear extinction law at visible wavelengths extends in the ultraviolet. This result is not compatible with standard extinction models, which all suppose a modification of the size distribution of interstellar grains and a flattening of interstellar dust’s extinction law at ultraviolet wavelengths. Nebulae IUE observations show no trace of Rayleigh scattering.

However, there is no way to decompose an extinction curve into the sum of a component of direct starlight ($\propto e^{-a/\lambda^p}$, $p \sim 1$) and a component of light scattered by dust grains ($\propto 1/\lambda^p e^{-a/\lambda^p}$, $p \sim 1$). Forward scattering by dust in the ultraviolet cannot explain the contamination by scattered starlight of the light received from reddened stars.

The analysis of a complete extinction curve $F/F_0$ of star HD46223, re-constructed from the near-infrared to the far-ultraviolet, shows that the spectral signature of its scattered light component varies as $1/\lambda^p$, with $p \sim 4$ (Zagury 2001a). This finding can be generalized to other directions (Sect. 10.2 and Zagury 2002). The scattering is of Rayleigh type, due to gas along the line of sight. Fig. 2 plots the ratio $f_s$ (dashed line) of scattered to direct light intensities found for HD46223.

There is a problem in observing both dust scattering as close as a few arc-seconds from a star and a significant amount of light scattered by gas in the complete forward direction. This problem can be resolved only if the scattering by gas is coherent in the forward direction. In this case, the irradiance at the position of the observer should no longer be in proportion to the number of scatterers in the line of sight, $N_X$, but increases as its square, $N_X^2$. Compared to incoherent scattering, the irradiance is enhanced by a factor $N_H$ (or $N_{H_2}$), that is, by $10^{20}$ to $10^{22}$ (average column densities for HI and H$_2$, as given in table 1 of Friedman et al. 2011).

9. Amount of scattered starlight

The magnitude of the scattered light component in the ultraviolet spectrum can be estimated by the gap between the observed extinction curve and the continuation of the linear extinction law at visible wavelengths.

The scattered light intensity, expressed in proportion to the direct light from the star, estimated for HD46223 (Fig. 2), is of the order of $0.015/\lambda^4$ ($\lambda$ in $\mu$m). Both components must be equally extinguished by interstellar dust extinction.

At near-infrared wavelengths, scattered starlight is 2% of HD46223’s flux. The ratio grows to 16% in the V band and to 30% in the B band. In the far-ultraviolet part of the spectrum, scattered starlight overpowers the star’s flux by nearly two orders of magnitude. The scattering compo-

---

*This estimation of the proportion of scattered starlight was derived assuming a $1/\lambda^p$ extinction law for interstellar dust. If the exact law is closer to $1/\lambda^p$, with $p > 1$, the proportion of scattered light should be larger.*
Fig. 2.— The ratio $f_s$ of scattered to direct starlight fluxes for HD46223. The extinction curve of HD46223, corrected for the exponential extinction by dust, is in dots. The solid black line $(1 + a/\lambda^4, a \sim 0.015$ if $\lambda$ is expressed in $\mu$m) fits the curve. The green dashed line represents the continuum of scattered starlight, $f_s = a/\lambda^4$.

The exact ratio of absolute to selective extinction by interstellar grains is unlikely to be the free parameter of interstellar extinction (Sect. 3) and is likely to be a constant, $R_{V0}$. Observed $R_V$ values may differ from $R_{V0}$ because of the presence of scattered starlight, which leads $A_V$ to be underestimated, and $A_B$ to be even more so (the scattering is stronger in the B-band). The exponent $p \sim 1$ for the extinction of direct starlight is smaller than that for scattered starlight ($p \sim 4$), which implies that observations underestimate the exact $A_B/A_V$ ratios. Since $R_V = 1/(A_B/A_V - 1)$, observed $R_V$-values should overestimate $R_{V0}$. The more scattered starlight there is in the spectrum of a reddened star, the greater the overestimation of $R_V$ should be. These consequences were illustrated in Zagury’s (2001a) case study of HD46223’s extinction spectrum.

10. Consistency

10.1. The value of $R_V$

$R_V$ is a measure of the relative strength of the extinction by large grains in the B and V bands ($\tau_B/\tau_V = 1 + 1/R_V$), and an indicator of the size distribution of interstellar dust (see Zagury & Turner 2012). It was recognized as a key parameter for interstellar dust in the 1960s (see Zagury 2012). Whether it is a constant or varies has been a long-standing debate among observers. In the wake of the CCM paper most studies have considered $R_V$ to be variable and the free parameter of interstellar extinction. Users of the Fitzpatrick & Massa parametrization, however, have usually adopted a constant $R_V = 3.1$ (Schlafly et al. 2010).

Turner & al. (2014) did find a minimum, $R_{V0} = 2.82$, in observed values of $R_V$. The corresponding extinction law $\tau_\lambda \propto 1/\lambda^{1.37}$ ($F/F_{\text{ref}} \propto e^{-1.14E(B-V)/\lambda^{1.37}}$) agrees with near-infrared observations (fig. 2 in Zagury & Turner 2012). Incidentally, it also coincides with atmospheric aerosol observations.

10.2. Agreement with observation

The true extinction law of interstellar matter should be well approximated by a quasi-linear law over the whole near-infrared to ultraviolet wavelength range. But, on top of the direct light from a reddened star, a telescope intercepts a component of scattered starlight (by HI or H$_2$ along the line of sight), which explains the departure from linearity of observed extinction curves. Both direct and scattered starlight are extinguished by interstellar dust and in the same proportion. Scattered starlight diminishes the impression of extinction and explains why the departure from linearity that can occur in the visible wavelength range (Nandy 1964) or in the far-ultraviolet (middle plot of Fig. 1) is always perceived as less extinction. When extinction is very low, scattering is very low, and the linear extinction law of interstellar dust emerges clearly over the whole spectrum. When extinction increases, scattering increases as well, and divergence from linearity is observed. This effect is especially pronounced in

---

3At this stage of research, the possibility that a slight variation of the exponent $p$ occurs from one end of the spectrum to the other cannot be excluded.
the ultraviolet spectrum. If the star is close to the scattering material, coherence is diminished or lost (Sect. 11.3); the linearity at visible wavelengths of the extinction curve tends to be continued in the ultraviolet domain, which is also what is observed.

The shape of an observed interstellar extinction curve is fixed by two parameters: the reddening E(B − V) and a free parameter which regulates the proportion of direct and scattered starlight (thus the size of the 2200 Å bump, Sect. 3). This free parameter is related to distances between the star, the interstellar cloud, and the observer in a way that remains to be determined.

Extinction in the Magellanic Clouds or in other galaxies need not be considered as singular. Linear extinction curves exist in the Galaxy. Lines of sight towards the Magellanic Clouds sample both local (Magellanic) clouds, which are infinitely close to the stars from the standpoint of the observer, and Galactic cirrus, relative to which Magellanic stars are infinitely far away. The coincidence of these two extreme situations along the same lines of sight is the only singularity of Magellanic extinction curves. This coincidence, together with the relatively low column densities of the Galactic cirrus in the line of sight, must explain why they have a reduced 2200 Å bump and smaller DIBs (Sect. 12).

The 1/\lambda^4 dependence of the scattered starlight component of extinction curves can be verified over a large sample of stars (Zagury 2002). After multiplication by \lambda^4, the far-ultraviolet spectrum of an extinction curve with a bump will generally be found to be an exponential with an exponent close to the one deduced from the visual extinction. The exact amount of dust extinction at visible wavelengths can thus be retrieved from the far-ultraviolet spectrum of a reddened star, and the relationship between visual and far-ultraviolet extinctions, empirically highlighted by CCM and Bondar et al. (2006), finds its physical meaning. Reddening E(B − V) obtained from the far-ultraviolet spectrum should be larger than the value observed in the visible wavelength range, the latter being slightly diminished because of the contribution from scattered starlight.

11. Observation and theory

11.1. Van de Hulst formula

In Section 4.3 of his book van de Hulst considers the scattering of an incoming plane-wave by a slab of identical, spherically symmetric particles. He sums, for the forward direction, the contributions of the scattered waves to the disturbance at the position of a far-away observer. He assumes that the particles are separated by distances larger than the wavelength (nX \lambda^3 \ll 1, with nX the density of the particles).

Van de Hulst’s formula leads to a ratio between the scattered and the un-reddened irradiances at the observer position (Zagury & Pellat-Finet 2012):

\[ \frac{I_s}{I_0} = \left( \frac{4 \pi^2 \alpha X N_X}{\lambda} \right)^2 = \frac{3}{8 \pi} n_X^2 \lambda^2 \sigma_X \]  

N_X is the column density of the particles, \( \alpha_X \sim \frac{9}{2} \sigma^3 \) their polarizability, a their mean size. Cross section \( \sigma_X \) is related to the polarizability by \( \sigma_X = \frac{8}{3} \pi k^4 \alpha_X^2 \) (Van de Hulst 1981, sect. 6.11). For molecular hydrogen the cross section comprises terms in \( k^6 \) and \( k^8 \) which have, in the ultraviolet spectrum, the same weight as the \( k^4 \) term (Dalgarno & Williams 1962). Eq. 1 anticipates a 1/\lambda^4 dependence for the irradiance of the scattered light if atomic hydrogen is the scatterer, with possible higher powers of 1/\lambda^2, if it is H2.

For directions with E(B − V) between 0.1 and 1, which are the directions where a bump at 2200 Å is most commonly observed, \( N_H \) is between 10^{21} and 5 \times 10^{22} cm^{-2} and \( N_{H_2} \) typically an order of magnitude less (Table 1 in Friedman et al. 2011). Condition \( nX \lambda^3 \ll 1 \) is doubtless verified, since densities should range from a few dozen particles (HI clouds) to a few hundred particles per cm^3 (molecular clouds) (Draine 2011). For \( \lambda = 1500 \text{ Å} = 1.5 \times 10^{-5} \text{ cm}, \sigma_H = 1.2 \times 10^{-25} \text{ cm}^2 \) and \( \sigma_{H_2} = 3.4 \times 10^{-25} \text{ cm}^2 \), \( I_s/I_0 \) anticipated by Eq. 1 is in the range 10^5 − 10^6.

11.2. Theoretical irradiance against measured power

A plane of oscillators creates a disturbance at an observer position that is fixed by the oscilla-
tor strength per unit area (Apps. A.1 and A.1.2). A region scaling with the first Fresnel zone contributes most to the disturbance.

The oscillator strength per unit area of the interstellar particles responsible for the scattered component of extinction curves is \((2\pi/\lambda)^2\alpha_x N_X\) (Van de Hulst 1981; Zagury & Pellat-Finet 2012). It is \(1/\lambda\) for a Huygens-Fresnel wavefront (App. A.1.2). The ratio of the two quantities should give the disturbance of the interstellar dipoles relative to Fresnel’s hypothetic molecules, which is what van de Hulst’s formula, Eq. [1] for the irradiance, expresses.

The formula contains no information on distances. This is predictable, since scattering from a first Fresnel zone is independent of the position of the zone between the source of light and the observer (Sect. A.1.2).

A refined representation of the interstellar cloud, which would also satisfy van de Hulst’s (unjustified in the textbook) requirement of a distance larger than the wavelength between the particles, would be that of a succession of wavefronts (instead of a single one) along the line of sight, all excited by the same plane wave. Each wavefront removes a very small fraction of the source energy, and the scattered waves from all wavefronts arrive with the same phase at the observer position. The expression of the irradiance (Eq. [1]), however, should not be modified. A further simplification of interest would be to limit the cloud to the first Fresnel zones of the wavefronts (for a star far away, a cylinder of radius \(\sqrt{\lambda L}\) and depth \(e = N_X/n_X\) seen edge on).

These representations underlie a similarity with Fresnel zone plates (App. A.2), with the contributing areas aligned along the line of sight instead of being in an orthogonal plane. Zone plate theory shows that the contribution of coherent sources at a focus may greatly enhance the irradiance (as the square of their number) without prejudicing energy conservation. For the far-field, the increase of the irradiance is balanced by the focalization of the scattered wave along the direction of the source. The power measured at the focus must remain a limited proportion of the power available for coherent scattering.

11.3. Qualitative discussion of the interstellar extinction problem

For a star infinitely far away, the region of the interstellar cloud that should contribute most to the scattered starlight at the observer position corresponds to an area of order \(\lambda L\). This area is subtended by a very small angle (\(\sim \sqrt{\lambda/L}\)), by far much smaller than the resolution a telescope can reach. Varying the size of the telescope will not modify the proportion of scattered starlight.

As for zone plates, the power measured by the telescope should also be found to be in proportion to the light extinguished within the area of coherence and increase as \(N_X\) (instead of \(N_X^2\)), thus in proportion to \(E(B - V)\) and to the size of the Fresnel zone \((\pi \lambda L)\) as seen by the observer. The variations of the average ratio of the size of the 2200 Å bump to \(E(B - V)\), which differs from one Galactic region to another (Meyer & Savage 1981), must result from the different distances of these regions from the sun (and not from variations of interstellar dust composition in different Galactic regions).

This conclusion is fully supported by the recent investigation of Schlaufly et al. (2016). The authors find that the mean observed Galactic \(R_V\) value depends on, and increases with, the distance of interstellar clouds (and no other parameter), and they assume that the distance is to be taken from the Galactic center. From the standpoint of the present study, however, the distance is more likely to be from the observer. The farther away the cloud, the larger its first Fresnel zone will be (with respect to the observer and for stars supposed to be far away on average), the more scattered starlight there is, implying larger observed mean \(R_V\) values (Sect. 10.1). These should also correlate with larger 2200 Å bumps.

Deviations from the average ratio of the size of the 2200 Å bump to \(E(B - V)\) within a Galactic
region, on the other hand, are more likely due to variations of star distances, or to an additional extinction (e.g., circumstellar extinction) in the line of sight. When the size of the first Fresnel zone shrinks due to the proximity of the star, the power available for coherent scattering, the proportion of scattered light in the spectrum of the reddened star, and the 2200 Å bump diminish.

A star may be comparatively close to the interstellar cloud and yet yield large Fresnel zones, meaning that distance star-cloud $D$ is large but that the cloud is much closer to the star than to observer ($D \ll L$), as occurs for Magellanic stars extinguished by local (Magellanic) clouds. The area of the first Fresnel zone, now of order $\lambda D$, is then small compared to $\lambda L$ and is fixed by the proximity of the star instead of by the observer-cloud distance.

Magellanic stars also have low column density Galactic cirrus (for which the stars are infinitely far away) in the line of sight. That DIBs are observed at the Magellanic Clouds redshift (Sect. 12) indicates that the 2200 Å bump and the scattered starlight component of Magellanic extinction curves should be attributed to Magellanic interstellar clouds rather than to Galactic cirrus. It follows that the reason why bumps and DIBs are weaker in observations of Magellanic stars is that Galactic cirrus in the line of sight are too light to give appreciable scattered starlight.

The observations discussed in this section seem to imply a symmetry in the roles played by the observer and the star in determining the amount of scattered starlight, and suggest that the free parameter of interstellar extinction curves is the size of the first Fresnel zone. Quantitatively, however, there is no straightforward way that I know of to move from the irradiance given by Eq. 1 to the power of the scattered starlight that a telescope will measure. The parallel drawn in this paper between Fresnel and interstellar oscillators, or between the forward scattering by identical dipoles and wave theory, can probably be pushed further. Abnormally large Fresnel zones, as found on astronomical scales, raise a problem for wave theory, the solution of which should help the analytical treatment of interstellar extinction curves.

12. Connection between the diffuse interstellar bands and the 2200 Å bump

The fact that the 2200 Å bump and the DIBs concern different wavelength domains and that the bump is a far more prominent feature has fostered a tendency to treat them independently. For instance, Herbig (1995) does not mention the bump in his review of research on DIBs.

Studies with a focus on the relationship between the bump and the DIBs have not always agreed on their correlation (Benvenuti & Porceddu 1989; Nandy & Thompson 1975; Wu et al. 1981). However, it can be inferred that although there is no strict proportionality between the DIBs and the bump, no proportionality among the DIBs exists either (Krelowski & Walker 1987; Herbig 1995; Xiang et al. 2012). And, as Friedman et al. (2011) point out, when the DIBs are observed, the bump is observed, and vice versa. When one is substantially weakened, the other is weakened as well. These correlations hold for the Galaxy as well as for the Magellanic Clouds.

Welty et al. (2006); Welty (2014) find that in the Magellanic Clouds, DIBs and the 2200 Å bump are both typically weaker for LMC and SMC directions than for Galactic sight lines with similar HI column density, by factors of 9 and 20, respectively. Cox et al. (2007) note that the presence or absence of DIBs in the Magellanic Clouds is linked to the presence or absence of a 2200 Å bump.

In the Galaxy, there are a few well known sightlines with anomalously weak DIBs: in Orion, stars HD36822 ($E(B-V) \sim 0.14$), HD37020 (0.37), HD37021 (0.54), HD37022 (0.34), HD37042 (0.42), HD37061 (0.52); HD147933 ($\rho$-Oph, 0.45); HD24534 (x Per, 0.56); HD29647 (1); HD34078 (AE Aur, 0.52); HD57061 (7 CMa, $E(B-V) \sim 0.16$); HD62542 (0.35); HD148184 (0.5); HD223385 (6 Cas, 0.67); Herschel 36 (0.87); Welty 2014 Dahlstrom et al. 2013; Friedman et al. 2011; Moutou et al. 1999; Snow 2002).

In all of these directions the 2200 Å bump is significantly weaker than expected from the reddening. The ultraviolet extinction curves of Herschel 36 in NGC 6530 and HD29647 in Taurus are remarkable because of the high $E(B-V)$ in these directions and a nearly absent 2200 Å bump (Snow & Seab 1980; Dahlstrom et al. 2013). The curves are of the intermediate type (middle plot) of Fig. 1.
the weakness of the bump in these curves coincides with the extension of the linear extinction law at visible wavelength down to the bump region. 

A relationship between the DIBs and the distance from the star to the reddening material has also been found for Galactic stars. Morgan (1944) associates a "systematically weakened" DIB $\lambda 4430$ to nebular material in the vicinity of stars. The tendency for DIB $\lambda 4430$ to increase with star distance also appears on a plot (fig. 6 in Duke (1951)) of the DIB's strength versus distance moduli for a sample of stars with similar reddening. From a survey of bibliographical sources Snow et al. (1995) conclude that

The general thrust of this literature is that the bands [DIBs] are either weak or absent in circumstellar regions of all descriptions, including both hot star and cool star envelopes.

The Galactic stars with weak DIBs mentioned above are generally bright in the far-infrared spectrum, which is an additional proof that part of the reddening material along the line of sight is close to the star. AE Aur, $\rho$-Oph, and CMa, are known to be close to or embedded in nebulae (Vos et al. 2011; Van den Berg 1966). The study by Dahlstrom et al. (2013) on Herschel 36 separates a foreground $(E(B-V) \sim 0.38)$ and a local $(E(B-V) \sim 0.49)$ extinction with comparable weights in the total reddening of the star.

The diffuse interstellar bands and the 2200 Å bump are concomitant in the spectrum of reddened stars and share the same properties: they tend to increase with the amount of interstellar material, do not depend on the reddening alone, and tend to disappear when interstellar matter is close to the star. At very low reddening (typically less than 0.08 mag.) neither the bump nor the DIBs are observed.

13. $H_2$ absorption lines and the Diffuse Interstellar Bands

Draine recently commented "It is embarrassing to have to admit that not a single one [DIB] has yet been identified" (Draine 2009). In fact, it was remarked as early as the 1970s that many DIBs match allowed transitions from electronically excited states of $H_2$ (Duardo 1970, 1971, 1974, 1975). The finding was independently made in more recent years and extended by P. Sorokin and J. Glownia (Sorokin & Glownia 2000, 2013). These theoretical investigations have been supported by laboratory experiments. These reveal an absorption spectrum of $H_2$ having "topological resemblance with observed DIB profiles" (Hinnen & Ubachs 1996), and coincidences between DIBs and $H_2$ resonances from ground state levels populated at low temperatures (Ubachs et al. 1997, Ubachs 2014).

Both Duardo and Sorokin & Glownia link the $H_2$ transitions that could produce the DIBs to a two-photon absorption of coherent light:

... a mechanism based entirely upon "passive" two-photon absorption by $H_2$ molecules cannot adequately explain the origin of the DIBs. As will be explained below, we currently assume that some form of coherent light wave structure is present in the $H_2$-containing cloud ... (Sorokin et al. 1998).

[Sorokin & Glownia were led to the conclusion that the DIBs and the bump are produced in the vicinity of O and B stars which is untenable with respect of the observed properties of the bump and of the DIBs (previous section and Snow (1995, 1998)).

That the Sorokin & Glownia mechanism cannot be retained should not disqualify their whole model, especially because of the striking correspondence between numerous DIBs and $H_2$ absorption lines. No other molecule has yet been
shown to provide any confirmed DIB identification, and H₂ is by far the most abundant molecule in interstellar clouds.

The bump’s energy, centered close to 5.7 eV, is about half the energy needed to photo-dissociate molecular hydrogen (Draine 2011, p. 419). A two-photon absorption, enabled by the coherence of the scattered light along the star-observer direction as required by the Sorokin & Glownia hypothesis, could explain the bump, leave unaffected the scattered light along the star-observer direction as required by the Sorokin & Glownia hypothesis, and provide the H₂ excited state needed for the absorptions at the DIB wavelengths.

Major difficulties would nevertheless remain in finding the exact selection rules, especially considering that the ground state of hydrogen is gerade, and that according to Ross & Jungen (1994) the first gerade-excited state of H₂ to be reached in a two-photon absorption is at 12.29 eV.

14. Further consequences

14.1. Star distances

Scattered starlight in the spectrum of reddened stars affects cosmic distance estimations because apparent magnitudes are overestimated. A bias also arises from the fact that standard extinction models tend to underestimate the extinction.

On the one hand, the presence of scattered starlight means that a fair amount of light is introduced into the beam of observation from directions other than the direction of the reddened star. The star appears brighter than it truly is; its observed apparent V-magnitude mᵥ is less than what it would be (mᵥ₀) without the scattered starlight. Neglecting the distinction between mᵥ and mᵥ₀, the star’s distance moduli is underestimated, which implies an underestimate of the star’s distance.

On the other hand, standard extinction models assume a smaller extinction than there really is. Visual reddening Aᵥ and color index E(B − V) are underestimated, while the absolute-to-relative-extinction parameter Rᵥ is overestimated (Sect. 10.1). As shown by Russell & Shapley (1914), even a moderate underestimation of the extinction leads to photometric distances that can be considerably overestimated.

A component of scattered starlight in the spectrum of reddened stars, or a deficiency of extinction if the scattered starlight is ignored, both describe the same observation - that is, the gap between observed extinction curves and the extension of the linear visible extinction towards the ultraviolet. Therefore, if Aᵥ₀ is the exact visual extinction, and with the notations defined above: $Aᵥ = Aᵥ₀ = mᵥ - mᵥ₀$.

The exact distance moduli for a reddened star of absolute V magnitude $Mᵥ$ is

$$mᵥ₀ - Mᵥ = 5 \log(d/10pc) + Aᵥ₀,$$

which can be rewritten as

$$mᵥ - Mᵥ = 5 \log(d/10pc) + Aᵥ₀ + (mᵥ₀ - mᵥ₀)$$

$$= 5 \log(d/10pc) + Aᵥ$$

Eq. 3 shows that the relative error $\Delta d/d$ is of order $E(B−V)\Delta Rᵥ/5$.

Eqs. 2 and 3 are different expressions of the distance moduli but lead to the same value for distance d, provided that Aᵥ (≠ Aᵥ₀) is correctly estimated. If standard extinction models do not introduce any specific error on distances, the more scattered starlight there is, the more models need to increase the value of $Rᵥ$ (≠ $Rᵥ₀$, which is a constant).

Empirical methods for the determination of $Aᵥ$ (Balázs et al. 2004, Cardelli, Clayton, & Mathis 1989) and $Rᵥ$ (Schlafly et al. 2016) have been used, resulting in impressively large error margins for photometric distances. Turner (2012) for instance, re-considering previous values of $Rᵥ$, finds distances that are cut down by a factor of two. It can be surmised that, since $Rᵥ ∼ 3$ is generally assumed to be canonical, photometric distances are more likely to be overestimated.

14.2. The PAH hypothesis

Poly-Aromatic-Hydrogenated molecules (PAHs) are part of nearly all three component models for interstellar extinction. Introduced in the 1980s to explain the infrared Unidentified Bands (UIBs, Leger & Puget (1984)), PAHs were quickly proposed to explain many of the interstellar extinction features over the whole spectrum that were not understood.

PAHs have been supposed to be the carriers of the far-ultraviolet rise of extinction curves (Desert,
of the 2200 Å bump (Steglich & al. 2010; Draine 2009), and of the DIBs (Duley 2006). They have also been thought to be the source of the Red Rectangle spectral features (Witt et al. 2009), and, according to Gordon et al. (1998), are responsible for some 50% of the Galactic red light.

PAHs probably have little to do with either the continuum of ultraviolet extinction or the 2200 Å bump (this paper). Their contribution to the DIBs is disputable (Sorokin et al. 1998; Ubachs 2014; Tielens 2008). They certainly do not contribute to the red light of Galactic cirrus (Juvela et al. 2008; Zagury et al. 1999), or a fortiori to the diffuse Galactic light (Zagury 2006). Furthermore, should the PAHs exist with the required properties, the observed fractional abundance of neutral PAHs would be \( \sim 10^{-9} \) less than hydrogen (Grebel et al. 2011), which is extremely low, certainly much lower than what models anticipate (of the order of \( 10^{-7} \) (Tielens 2008)).

Despite considerable theoretical and laboratory efforts to match their chemistry to interstellar issues, the very existence of PAHs can legitimately be questioned. As suggested by the title of the 2010 Toulouse symposium “PAHs and the Universe: A Symposium to Celebrate the 25th Anniversary of the PAH Hypothesis” PAHs remain hypothetical constituents of the interstellar medium.

15. Conclusion

What does an observer sees when s/he observes a star behind an interstellar cloud? If the telescope gathers only the direct light from the star extinguished by interstellar particles, a minimum of three different types of particles, in proportions that vary from one interstellar cloud to another, each type extinguishing light in a particular spectral range, are necessary to explain the observed visible-ultraviolet interstellar extinction spectrum. There are logical incompatibilities between this assumption and observation.

The sole alternative is that scattered starlight is mixed with the direct light we receive from reddened stars and substantially modifies their extinction spectrum. In addition to the spectrum of a reddened star, the observer retrieves the first order diffraction pattern of hydrogen atoms or molecules in the cloud in the line of sight.

Fresnel’s theory can be used to overcome most of the objections that the attribution of the non-linearity of extinction curves in the ultraviolet to a scattering process can raise. It provides the elementary ideas that explain the observed properties of the scattered light component in the spectrum of reddened stars, its magnitude, and the reason why it becomes appreciable only when distances are extremely large. It also indicates that, in addition to column density, the key parameter of interstellar extinction is related to the size of the first Fresnel zone at the cloud position, as seen by the observer. However, diffraction from very large Fresnel zones still creates a challenge for the theory, which does not provide a straightforward fit for interstellar extinction curves.

Over the years this alternative interpretation of the continuum of extinction curves has been confirmed by different types of observation. These include the ultraviolet spectrum of nebula, which does not indicate a discontinuity between the visible and the ultraviolet spectrum of the scattering cross-section of interstellar dust; the ultraviolet extinction law of stars with very little reddening, which is linear over the whole spectrum; the analysis of the relationship between the extinctions in the visible and the far-ultraviolet parts of the spectrum; and the study of Magellanic extinction curves, which tends to prove the universality of the extinction law of interstellar matter. That observed values of \( R_V \) depend on the distance of interstellar clouds is another finding that standard extinction models can hardly accommodate.

Three implications are worth noting:

1. The three major features of interstellar extinction (the deviation of the continuum from linearity in the ultraviolet spectrum, the 2200 Å bump, and the diffuse interstellar bands) are intimately connected. They have the same properties (e.g. they cancel at very low reddening or when the interstellar matter is close to the reddened star) and are concomitant. The bump has the peculiarity of being a selective extinction of the scattered starlight component of extinction curves.

2. Three-component models and the assumption that scattered starlight contaminates
the spectrum of reddened stars are mathematically equivalent, insofar as distance estimations are concerned. Classical (no scattered starlight) derivations of cosmic distances underestimate the true extinction and need to overestimate the $R_V$ parameter. The adoption of the canonical $R_V = 3.1$ value with a standard extinction model, for instance, can lead to overestimating photometric star distances.

3. This revision of interstellar extinction challenges the basis of traditional interstellar dust models, i.e. the separation of extinction curves into three distinct wavelength domains, the justification of which has led to the search for hypothetical molecules such as the PAHs. The existence (with the required properties) of these molecules is unnecessary and doubtful. They are likely to meet the fate of Fresnel’s "mol´ ecules eth´ er´ ees" and other such unsuccessful quests in the history of physics for particles that do not exist. This is all the more likely for particles whose density should be $10^{-9}$ the density of $\text{H}_2$ (Gredel et al. 2011), in a medium, the interstellar medium, that is a near perfect vacuum.

In the framework developed in this paper, I have not questioned the nature of the interstellar dust grains responsible for the extinction of starlight. It is more likely to be the size distribution, rather than the chemical composition of the interstellar grains or molecules, that produces the direction-independent, quasi-linear extinction law over the whole near-infrared to far-ultraviolet spectrum. Whether interstellar dust is a mixture of graphite particles or silicates (Hoyle & Wickramasinghe 1962, 1969), or other particles, does not affect the present work.

Hydrogen (atomic and/or molecular) should be the major and probably unique agent of the remarkable properties of interstellar extinction that are observed on top of the linear dust extinction: the ultra-violet departure from the linear dust extinction law, the 2200 Å bump, and the DIBs. Item 1 above implies that DIB research cannot be conducted independently from a more general reflection on the two other major features (the continuum and the bump) of interstellar extinction.

Sect. 13 recalled that molecular hydrogen is the only molecule to which a large number of DIBs can be assigned, a fact that would be worth investigating more deeply. It was suggested in this paper that the 2200 Å bump was a two-photon absorption by molecular hydrogen of coherent scattered starlight. From the excited state, molecular hydrogen absorption at the DIBs frequencies becomes possible.

acknowledgement

I thank David Turner for pointing a mistake in a previous version of Sect. 14.1 (on star distances), and Laleh Safari, Filippo Fratini, Kari Jänkälä, for introducing me to the difficulties the bump and the DIBs can raise in the context of molecular hydrogen theory.

REFERENCES

Balázs L.G., Abrahám P., Kun M., Kelemen J., Tóth L.V.: 2004, A&A, 425, 133
Benvenuti P., Porceddu I.: 1989, A&A, 223, 329
Bethe H.A.: 1944, Phys Rev, 66, 163
Boivin A.: 1952, JOSA, 42, 60
Bondar A., Galazutdinov G.A., Patriarchi P., & Krelowski J.: 2006, J Korean Astr Soc, 39, 73
Born M, Wolf E.: Principles of optics, Cambridge, Cambridge University Press. 1999 (7th edition)
Bradley J., et al.: 2005, Sci, 307, 244
Campbell E.K., Holz M., Gerlich D., Maier J.P.: 2015, Nat, 523, 322
Cardelli J.A., Clayton G.C., & Mathis J.S.: 1989, ApJ, 345, 245 (CCM)
Childers H.M., Stone D.E.: 1969, Am Jour Phys, 37, 721
Cox N.L.J., et al.: 2007, A&A, 470, 941
Dahlstrom J. et al.: 2013, ApJ, 773, 41
Dalgarno A., Williams D.A.: 1962, ApJ, L36, 691
Désert F.X., Boulanger F., & Puget, J.L.: 1990, A&A, 237, 215
Draine B.T.: Physics of the Interstellar and Intergalactic Medium, Princeton Series in Astrophysics: Princeton University Press. 2001

Draine B.T.: Cosmic Dust - Near and Far, ASP Conference Series, 414, 453; Henning T., Grn E., Steinacker J. Eds; San Francisco: Astronomical Society of the Pacific, 2009

Duardo J.A: International Symposium on Molecular Spectroscopy 1970 [http://hdl.handle.net/1811/8512]

Duardo J.A: International Symposium on Molecular Spectroscopy 1971 [http://hdl.handle.net/1811/8723]

Duardo J.A: International Symposium on Molecular Spectroscopy 1974 [http://hdl.handle.net/1811/16291]

Duardo J.A: International Symposium on Molecular Spectroscopy 1975 [http://hdl.handle.net/1811/9315]

Duke D.: 1951, ApJ, 213, 100

Duley W.W.: 2006, ApJ, 643, L21

Feynman R.P., Leighton R.B., Sands M.: The Feynman Lectures on Physics, Vol. 1, Reading: Addison-Wesley, 1964

Fitzpatrick E.L., & Massa D.: 1988, ApJ, 328, 734

Fresnel A.: Oeuvres Complètes d’Augustin Fresnel, Tome I, Paris, 1866

Friedman S.D., et al.: 2011, ApJ, 727, 33

Gordon K.D., Witt A.N., Friedmann B.C.: 1998, ApJ, 498, 522

Gredel R., et al.: 2011, A&A, 530, 26

Greenberg J.M., Chlewicki G.: 1983, ApJ, 272, 563

Greenberg J.M.: 2000, Sci Am, Dec., 70

Greenstein J.L.: 1938, ApJ, 87, 151

Hecht E.: Optics, Reading, Massachusetts Addison-Wesley. 2003 (4th edition)

Herbig G.H.: 1995, ARAA, 33, 19

Hinnen P.C., Ubachs W.: 1995, Chem Phys Let, 254, 32

Hobbs L.M., et al.: 2009, ApJ, 705, 32

Hoyle F., Wickramasinghe N.C.: 1962, MNRAS, 124, 417

Hoyle F., Wickramasinghe N.C.: 1969, Nat, 223, 459

Juvela M., et al.: 2008, A&A, 480, 445

Kreloowski J., Walker G.A.H.: 1987, ApJ, 316, 449

Léger A., Puget J.L.: 1984, A&A, 137, L5

Massa D., Fitzpatrick E.L.: 1986, ApJS, 608, 305

Meyer D.M., Savage B.D.: 1981, AJ, 248, 545

Moutou C., Kreloowski J., d’Hendecourt L., Jaroszczak J.: 1999, A&A, 351, 680

Morgan W.W.: 1944, AJ, 51, 21

Mulas G., Zonca A., Casu S., Cecchi-Pestellini C.: 2013, ApJS, 207, 7

Nandy K.: 1964, Pub Roy Obs Ed, 3, 142

Nandy K., Thompson G.I.: 1975, MNRAS, 173, 237

Ross S.C., Junger Ch.: 1994, Phys. Rev. A, 50, 4618

Russell H.N., Shapley H.: 1914, ApJ, 40, 417

Savage B.D.: 1975, ApJ, 199, 92

Schlafly E.F., et al.: 2010, ApJ, 725, 175

Schlafly E.F., Peek J.E.G., Finkbeiner D.P., Green G.M.: 2016, arXiv: 1612.02818

Seab C.G., Snow T. P., Joseph C.L.: 1981, ApJ., 246, 788

Sitko M.L., Savage B.D., Meade M.R.: 1981, ApJ., 246, 161

Snow T. P.: 1995, Chem. Phys. Lett., 245, 639

Snow T. P.: 1998, Faraday Disc., 109, 230

Snow T. P., et al.: 2002, ApJ., 573, 670
Snow T. P., Bakes E.L.O., Buss R.H. Jr., Seab C.G.: 1995, A&A, 296, L37
Snow T. P., Seab C.G.: 1980, ApJ., 242, L83
Sorokin P.P.: 2013, Opt Comm, 287, 234
Sorokin P.P., Glownia, J. H., Ubachs, W.: 1998, Faraday Disc., 109, 137
Sorokin P.P., Glownia, J. H.: 2000, CaJPhys, 78, 461
Sorokin P.P., Glownia, J. H.: 2005, IBM Research Report RC23641
Sorokin P.P., Glownia, J. H.: 2006, arXiv.org, 0608092
Steglich M., Jäger C., Rouillé G., Huiskes F., Mutschke H., Henning Th.: 2010, ApJ, 712, L16
Stone J.M.: Radiation and optics; an introduction to the classical theory., New York: McGraw-Hill, 1963
Tielens A.G.G.M.: 2008, ARAA, 46, 289
Turner D.G.: 2012, Ap&SS, 337, 303
Turner D.G., Majaess D.J., Balam D.D.: 2014, CaJPh, 92, 1696
Ubachs W.: 2014, IAUS, 297, 375
Ubachs W., Hinnen P.C., Reinhold E.: 1997, ApJ, 476, 193
Van de Hulst H.C.: Light scattering by small particles, New York: Dover. 1981
Van Den Berg S.: 1966, AJ, 71, 990
Valencic L.A., Clayton G.C., Gordon K.D.: 2004, ApJ, 616, 912
Vos D.A.I., et al.: 2011, A&A, 533, A129
Welty D.E., et al.: 2006, ApJSS, 165, 138
Welty D.E.: 2014, IAUS, 297, 153
Witt A.N., et al.: 2009, ApJ, 693, 1946
Wu C.C., York D.G., Snow T.P.: 1981, AJ, 86, 755
Xiang F., Liu Z., Yang X.: 2012, PASJ, 64, 31
Zagury F., Boulanger F., Banchet V.: 1999, A&A, 352, 645
Zagury F.: 2000a, NewA, 5, 211
Zagury F.: 2000b, NewA, 5, 285
Zagury F.: 2001a, NewA, 6, 403
Zagury F.: 2001b, NewA, 6, 471
Zagury F.: 2002, NewA, 7, 117
Zagury F.: 2005, NewA, 10, 237
Zagury F.: 2006, MNRAS, 370, 1763
Zagury F.: 2007, Ap&SS, 312, 113
Zagury F.: 2012, AN, 333, 160
Zagury F., Pellat-Finet P.: 2012, Opt Comm, 285, 4001
Zagury F., Turner D.G.: 2012, AN, 333, 640
Zagury F.: 2013, AN, 334, 1107

---

This 2-column preprint was prepared with the AAS LaTeX macros v5.2.
A. Diffraction theory as the basis of coherent forward Rayleigh scattering

Fresnel’s theory, the first theory to account for diffraction phenomena, lies behind scattering theory. The basic idea (Huygens’ principle) supposes the existence of a medium of small oscillators (“molécules éthérées”) which transmit the light vibration, preferentially in the forward direction. Light propagates through the excitation of the successive layers (wavefronts) of oscillators centered on the source of light. The specific nature of these oscillators and the characteristics of the medium were never clarified, for the good reason that they do not exist.

Modern presentations of wave theory rely on the estimation of the contribution of a small area $\delta S$ of a wavefront to the irradiance at an observer’s position, or focus, $P$. Area $\delta S$ (at distance $D$ from the source and $l$ from the observer) needs to be neither too small (Sect. A.3), nor too large (to avoid appreciable phase-lags within $\delta S$) compared to the wavelength. The contribution $u_{\delta S}$ of $\delta S$ to the disturbance $U_0$ at $P$ is fixed by the size of the area (the number of oscillators is proportional to the area) and by the path-difference $\Delta_{\delta S}$ between the trajectory light follows from the source to the observer passing by $\delta S$, $D + l$, and the straight source-observer distance $D + L$.

Dismissing the $e^{i\omega t}$ time-dependence, the disturbance $u_{\delta S}$ consists in an amplitude and a phase-lag term. The amplitude, $\epsilon_\lambda A\delta S/(2\pi)$, is proportionate to the radiation field at the wavefront location ($A\delta S/D$) and propagates as the inverse-distance $1/l$ from $\delta S$ to the observer. The proportionality coefficient $\epsilon_\lambda$ depends on the wavelength and stands for the strength per unit area and unit radiation field of Fresnel’s oscillators in the forward direction.

The phase-lag term $e^{i\phi_{\delta S}}$ of $u_{\delta S}$ differentiates the contributions of different areas according to their position on the wavefront. If $r$ is the distance from $\delta S$ to the source-observer axis

$$\Delta_{\delta S} = \frac{r^2}{2} \left( \frac{1}{D} + \frac{1}{L} \right)$$
$$\phi_{\delta S} = \frac{2\pi}{\lambda} \Delta_{\delta S} = \pi r^2 \frac{D + L}{\lambda DL}$$
$$u_{\delta S} = \frac{A \epsilon_\lambda}{D} e^{i\phi_{\delta S}} \delta S$$

The irradiance that area $\delta S$ alone would induce at $P$ is in proportion to $\delta S^2$ although the power crossing the area is proportional to $\delta S$. Therefore, $N$ identical neighboring areas with negligible phase differences at $P$ contribute as $N^2\delta S^2$ to the irradiance at $P$, while the power crossing the areas increases as $N\delta S$. This implies a concentration of power at the focus and a depletion elsewhere that underlie diffraction phenomena.

A.1. The first Fresnel zone

A.1.1. Definition

The first Fresnel zone is the disk centered on the direction of the source within which contributions of a wavefront cooperate constructively at the position of the observer. Light paths between the source and the observer passing through any two points within the zone differ by less than half the wavelength ($\phi_{\delta S} < \pi$, $\Delta_{\delta S} < \lambda/2$). Successive Fresnel zones are defined by rings of constructive interferences (from positions within the ring) at the observer position.

At distance $L$ from the observer and $D$ from the source, the radius and area of the first Fresnel zone are

$$r_\lambda = \left( \frac{\lambda DL}{D + L} \right)^{0.5}$$
$$S_\lambda = \pi \lambda \frac{DL}{D + L}$$

For a given distance between the source and the observer, $S_\lambda$ is small close to the source and close to the observer, and maximal ($S_\lambda = \pi \lambda L/2$) in-between. But the largest size a Fresnel zone can reach at a given
distance from the focus, \( S_\lambda = \pi \lambda L \), is obtained when the source of light is a plane wave (the source is infinitely far away and the wavefront is a plane).

The order of magnitude for the radius of a first Fresnel zone is typically a few millimeters in laboratory experiments, 100 m within the solar system, 1000 km a few hundred parsecs away.

The Fresnel zone of order \( j \) is the region of the wavefront within which the phase shift \( \varphi_\delta S \) is in-between \((j-1)\pi/2\) and \(j\pi/2\). It is limited by the rings of radius \( r_j \) and \( r_{j+1} \) with

\[
\begin{align*}
  r_1 &= r_\lambda \\
  r_j &= j^{0.5} r_\lambda
\end{align*}
\]

All Fresnel zones have the same area \((\pi r^2_\lambda)\), but the thickness of the ring they delimit decreases quickly (as \( r_\lambda/\sqrt{j} \)) with the increasing order \( j \) of the zone.

A.1.2. Contribution of a first Fresnel zone to the irradiance

Should a first Fresnel zone be divided into \( N \) rings of equal area \( \delta S = S_\lambda/N \), the phase-lag of ring \( j \) is \( \varphi_j = j\pi/N \). The disturbance at \( P \) due to the first zone alone is \((\text{Eq. A3 and } N \gg 1)\)

\[
U_1 = \frac{2i A \epsilon_\lambda}{\pi D L} \sum_{j=0}^{N-1} \delta S e^{i\varphi_j} = 2i \frac{A \epsilon_\lambda}{D + L} \delta S
\]

since \( \sum_{j=0}^{N-1} e^{i\varphi_j} = 2iN \). Disturbance \( U_1 \) from a first Fresnel zone is independent of the position of the wavefront between the source and the observer and is, as expected, proportional to disturbance \( U_0 \) at \( P \) (the observer’s position).

Fresnel argued that a limited part (characterized by the size of the first zone) of the wavefront around the source-observer axis contributes most to the irradiance at \( P \), since a small solid angle issued from the observer position intercepts an increasingly large number of Fresnel zones as it shifts away from the axis, and their contributions tend to cancel out. In addition, the disturbance from any half of a Fresnel zone, except for the first half of the first Fresnel zone, is annihilated by the half from one of the two nearest zones. Accordingly, disturbance \( U_0 \) at \( P \) should be the disturbance due to half the first zone alone and half the disturbance due to the whole first zone.

Fresnel’s argument neglects the phase variations within a zone, and was eventually refined \([\text{Born 1999, Hecht 2003}]\): the amplitude of the disturbance at \( P \) is half the amplitude of the disturbance from the first zone and \( 1/\sqrt{2} \) times the disturbance’s amplitude due to half the first zone. The irradiance at \( P \) is \( 1/4 \) the irradiance due to the first Fresnel zone and half the irradiance due to half of the zone.

Equations (Eqs. A1 to A8) and most reasonings thus far apply to any set of identical dipoles, regardless of the particular case of light diffraction. The value of \( \epsilon_\lambda \) is fixed by the nature of the oscillators.

For Fresnel oscillators \(|U_1| = 2|U_0|\) implies \( \epsilon_\lambda = 1/\lambda \) and a quarter of a period phase shift between \( U_1 \) and \( U_0 \) (Eq. A8). From Eq. A3

\[
\begin{align*}
  U_1 &= \frac{2Ai}{L + D} = 2iU_0 \\
  u_\delta S &= \frac{A}{XL\varphi} e^{i\varphi_\delta S} \delta S
\end{align*}
\]

Eq. A10 gives the disturbance at \( P \) per unit area of the wavefront, \( u_\delta S/\delta S \).

If \( N \) identical small areas \( \delta S \) cover the first Fresnel zone, the disturbance they create at the observer position \( P \) will necessarily be \( U_1 = \Sigma u_\delta S = \frac{2i}{N} S_\lambda |u_\delta S| \). The irradiance at \( P \) is \( 1/4 \) the irradiance \( I_1 \) due
to the first Fresnel zone alone, and equals the irradiance due to any sub-set of the first zone with identical areas, as they had no phase lag at $P$, divided by $\pi^2$:

$$I_0 = \frac{1}{4} I_1 = \left( \frac{1}{\pi} \right)^2 N^2 |u_S|^2 = \left( \frac{1}{\pi} \right)^2 S_N^2 \left| \frac{u_S}{S^2} \right|^2$$  \hspace{1cm} (A11)

A remarkable property of first Fresnel zones is that their contribution to the disturbance (equally to the irradiance) at $P$ depends neither on the size of the zone (its position between the source and the observer) nor on the wavelength. The importance for optics of first Fresnel zones was acknowledged by Van de Hulst (1981) in the following terms:

The amplitude at a distance $l$ beyond a plane wave front is such as if an area $\lambda l$ of the wave front contributes with equal phase and the remaining part of the wave front not at all ... A pencil of light of length $l$ can exist only if its width at its base is large compared to $\sqrt{\lambda L}$.

### A.2. Zone plates

Irradiance at a focus is amplified by a factor of 4 if the light from the first Fresnel zone alone is selected. The necessary counterpart of the increase of power at the focus is that it is concentrated on a small disc, the Airy disk, around the focus.

If $I_1(q)$ is the irradiance in the focal plane at distance $q$ from the axis, due to diffraction of a plane wave by the first Fresnel zone ($r_1 = \sqrt{\lambda L}$),

$$I_1(q) = I_1(0) \left[ 2 \frac{J_1(z)}{z} \right]^2$$ \hspace{1cm} (A12)

\begin{equation}
\left( z = kr_1 \frac{q}{L} = 2\pi \frac{q}{\sqrt{\lambda L}} \right)
\end{equation} \hspace{1cm} (A13)

$J_1$ is the Bessel function of the first kind of order 1.

The first minimum of $|J_1(z)/z|$ is for $(z = 3.83, q_1 = \frac{\lambda}{\pi} \sqrt{\lambda L})$ and limits the Airy disk of area $Q_1 = \frac{3.83}{\pi} \lambda L$.

The power $P_1$ across the spot is

$$P_1 = I_1(0) \int_{z=0}^{z=3.83} \left[ 2 \frac{J_1(z)}{z} \right]^2 2\pi q dq$$

$$= \frac{\lambda L}{\pi} \int_{0}^{3.83} \frac{J_1(z)^2}{z} dz I_1(0)$$

$$\simeq \frac{0.4}{\pi} \lambda L I_1(0) = \frac{1.6}{\pi} \lambda L I_0$$ \hspace{1cm} (A14)

In contrast to the irradiance ($I_1 = 4I_0$ at the focus), $P_1$ depends on the area of Fresnel zones. It remains less than the power $\pi \lambda L I_0$ crossing the Fresnel zone.

Irradiance at the focus can be increased even more by adding the cooperative disturbances from Fresnel zones of the same parity. A zone plate comprising $N$ zones of the same parity has a theoretical irradiance at the focus $I_N(0) = N^2 I_1(0) = 4N^2 I_0$. The irradiance is amplified by $4N^2$. Since the 1950s zone plates with hundreds of Fresnel zones have been fabricated in the laboratory. A zone plate with 500 zones for instance amplifies the irradiance by a factor $10^6$.

The counterpart to this great increase in the irradiance is a concentration on a limited area around the focus, $s_N$, of the power crossing the focal plane. Should it be supposed that the power across $s_N$ is nearly $I_N(0)s_N$ and remains a non-negligible part of the power $P_N = NP_1 = NS_1 I_0$ flowing through the zone, $s_N$ must be of the order $S_1/N$ and must decrease as $1/N$ (since $I_N(0) = 4N^2 I_0$).
Zone plate theory [Boivin 1952; Childers & Stone 1969] proves that the distribution of light in the focal plane of a zone plate continues to be well approximated by the Airy diffraction pattern of a circular aperture having the size of the zone plate\(^7\) (radius \(a = r_{2N-1} \simeq \sqrt{2N\lambda L}\), area \(S_{2N} = 2\pi N\lambda L\)). Accordingly, the irradiance in the focal plane at distance \(q\) from the axis is

\[
I_N(q) \simeq I_N(0) \left(\frac{2}{z} J_1(z)\right)^2
\]

with

\[
z = kr_{2N-1} \frac{q}{L} = 2\pi q \sqrt{\frac{2N}{\lambda L}}
\]

The radius of the bright focal spot is obtained for \(z = 3.83\) and worth \(q_N = \frac{1.91}{\pi} \sqrt{\lambda L/(2N)}\). Its area, \(Q_N = \frac{3.84}{\pi} \lambda L/N\), diminishes as \(1/N\) (as anticipated above), and increases with the size of the first Fresnel zone.

The power \(P_N\) across the focal spot is calculated as for Eq. A14

\[
P_N = \left(\frac{0.54}{\pi^2} Q_N\right) I_N(0)
\]

\[
= \frac{2.15}{\pi^2} N^2 Q_N I_0 = \frac{0.4}{\pi^2} S_N I_0
\]

\(Q_N I_0\) is the power that would be measured across the bright spot if there were no zone plate; \(S_N I_0\) is the power crossing the zone plate.

The power \(P_N\) an observer measures over \(Q_N\) varies as \(N^2\) times the power that would be measured without the zone plate. It nevertheless remains in proportion to the available power: the \(\propto N^2\) growth of the irradiance at the focus is compensated by the \(1/N\) decrease of the area of the bright central spot. Energy conservation is ensured, since the power crossing \(Q_N\) remains in a constant ratio \((\ll 1)\) with the power on the zone plate.

Diffraction by a zone plate tends to align the direction of the diffracted light with the direction of the source wave, and to focalize the available power within a solid angle \(\Omega_N = Q_N/L^2 = 2\lambda/(\pi NL) = 2\lambda^2/S_N\).

### A.3. Diffraction by obstacles (particles or apertures) with small dimensions compared to the wavelength

Lorentz’s atomic dipoles may be what matches best the idea of Fresnel’s oscillators [Stone 1963]. Unlike areas \(\delta S\) with a size comparable to the wavelength, dipoles have a nearly isotropic phase function (within a factor of 2 between the back and forward directions). The disturbance due to a dipole depends on the wavelength as \(1/\lambda^2\) (instead of \(1/\lambda\)), and the irradiance as \(1/\lambda^4\) [Van de Hulst 1981; Stone 1963].

Theory also shows that the extension of Eq. A10 fails when applied to apertures with dimensions that are small compared to the wavelength [Bethe 1944]. A very small area diffracts light with the same \(1/\lambda^2\) wavelength dependency of the disturbance as a dipole does. The disturbance due to a dipole or a small aperture is \(\propto \lambda^{-2} a^3\) (irradiance \(\propto \lambda^{-4} a^6\)), where \(a\) is the typical size of the dipole/aperture.

To ensure continuity between the two regimes (small or large apertures/obstacles), several small diffracting apertures/obstacles covering a larger area of order \(\lambda^2\) must yield the forward disturbance of Eq. A10. This can only occur if a thickness of order \(\lambda\) is attributed to Huygens-Fresnel wavefronts, and if the \(a^3\) term in the disturbance created by a dipole is interpreted as corresponding to its volume \(\delta V\). The disturbance created at a focus by a set of apertures or obstacles smaller than the wavelength is then \(\delta u \propto \lambda^{-2} \delta V\) (since \(\delta S \sim \delta V/\lambda\) in Eq. A10).

\(^7\)The property can be understood because when \(N\) is large Fresnel rings become extremely thin.
If a thickness $\lambda$ is attributed to wavefronts, and if Fresnel’s oscillators (radius $a_F$, density $n_F$, polarizability $\alpha_F \simeq \frac{9}{2}a_F^3$, column density of a wavefront $N_F = \lambda n_F$) had any existence at all, the oscillator strength per unit area of a wavefront would be $(2\pi/\lambda)^2 \alpha_F N_F = (2\pi/\lambda)^2 \alpha_F \lambda n_F$ on the one hand (Sect. 11.2), and $1/\lambda$ on the other. Their radius and density would be related by: $18\pi^2 n_F a_F^3 \simeq 1$. 

