A review of the properties of the scattered starlight which contaminates the spectrum of reddened stars

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Abstract

When a star is observed behind an interstellar cloud of sufficient column density, we do not observe the direct light from the star, which is totally extinguished. Rather, we see only starlight scattered at small angles from the star.

I use several papers published in New Astronomy to recount the different steps which permit understanding how, and under which conditions, scattered starlight can be more important than direct starlight in the spectrum of a reddened star. Associated problems -the fit of the extinction curve, the nature of the scatterers (small grains, or, atoms or molecules from the gas), the 2200 Å bump- are also, briefly, discussed.

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1 Introduction

In a preceding paper (Zagury, 2002b) I have reviewed several arguments which prove that the standard interpretation of the extinction curve, upon which all interstellar dust models are based, does not agree with observation. If the standard theory is wrong, it must be that the spectrum of reddened stars comprises in the UV an important part of starlight scattered at small angular distance from the stars (Zagury, 2002b).

We already know that all the intensity of this light is concentrated within 0.3” from the star (Zagury, 2002b). I will use results from previously published papers.
papers to pinpoint the nature of this light and of the scatterers. This forecasts new directions of research which are discussed in section 6.

2 The spectrum of the scattered light

2.1 Importance of the scattered light

The importance of the scattered light was roughly estimated in Zagury (2000b). In the UV spectrum of stars with an intermediate reddening ($E(B-V) \sim 0.3$) we can separate the direct starlight, which still dominates the near-UV part of the spectrum, and the scattered starlight, clearly superimposed on the tail of the exponential decrease of the direct starlight. The scattered starlight can reach $\sim 15 - 20\%$ of the direct starlight corrected for extinction (Zagury, 2000b). As a comparison, the light we receive from the star is extinguished by $\sim e^{-2E(B-V)/\lambda}$ (\(\lambda\) in \(\mu\)m), if the linear visible extinction extends to the UV. For $1/\lambda \sim 6\mu\text{m}^{-1}$, and $E(B-V) = 0.3$, the direct starlight is less than 3\% of what it would be if there was no extinction. It is under $3/1000$ for $E(B-V) = 0.5$. We see that if the reddening is sufficient, the scattered starlight largely dominates the direct starlight.

2.2 Wavelength dependence of the scattered light

Since scattering occurs very close from the star, scattered and direct starlights must cross the same medium, thus being extinguished in a similar manner. By correcting the spectrum of a reddened star normalized by the spectrum of a non-reddened star of same spectral type (the reduced spectrum of the star, Zagury (2000b)) we expect to find a constant in the visible (1 if the non-reddened star and the reddened one are identical and at the same distance from the observer), and a spectrum which caracterizes the scattered light in the UV.

The method was applied (Zagury, 2001a) to the reduced spectrum of HD46223 ($E(B-V) \sim 0.5$) which was established from the visible to the far-UV. It was finally found that, outside the bump region, the reduced spectrum of HD46223 is the sum of two components (see figure 1, adapted from Zagury (2001a)). One is the extinction of the direct starlight, proportional to $e^{-2E(B-V)/\lambda}$. The second is the scattered light, $\propto \lambda^{-4}e^{-2E(B-V)/\lambda}$. Hence, if we correct the reduced spectrum of HD46223 for extinction we find that the scattered light depends on wavelength as $\lambda^{-4}$.
3 The relation between visible and far-UV extinctions

If the scattered starlight depends on wavelength as $\lambda^{-4}$, the product of the reduced spectrum of a reddened star by $\lambda^4$ will be proportional to $e^{-2E(B-V)/\lambda}$ in the far-UV.

For a number of reddened stars, I have compared (Zagury, 2002a) the value $E_{uv}$ of $E(B-V)$ found for the slope of the product (reduced spectrum)$\times\lambda^4$ in the far-UV, to the value $E_{vis}$ given by the spectral type of the stars and $B-V$. The agreement between $E_{uv}$ and $E_{vis}$ is excellent, with a tendency for $E_{uv}$ to be larger than $E_{vis}$. This tendency is expected since scattered light, when it appears in the visible, diminishes the slope of the visible extinction.

This general relation between visible and UV extinctions is incompatible with the standard theory of extinction. According to which, there is no relation between the proportion of large grains responsible for the visible extinction, and the proportion of molecules responsible for the far-UV rise of the extinction curve (Jenniskens & Greenberg, 1993).

4 Scattering at null angle and scattering by the nebulae

In the UV, the scattering of starlight by a nebula follows a $1/\lambda$ law (Zagury, 2000a, 2002b). The particles responsible for the brightness of the nebulae are not the same as the particles responsible for the additive component of scattered light in the spectrum of reddened stars, which scatter starlight as $1/\lambda^4$.

Light scattering as $1/\lambda$ is produced by large grains which preferentially scatter light forward. A $1/\lambda^4$ scattering cross section (Rayleigh scattering) implies the presence of small particles, with a quasi-isotropic phase function. Why is the near-isotropic scattering by small particles detected in the forward direction only, and not in the nebulae, while the forward scattering by the large grains is observed at larger angles but is negligible in the spectrum of reddened stars?

5 Coherent scattering at very small angle

There is one possible answer to the preceding questions, and it is the only one I have found which satisfies all the requirements imposed by observation.

While scattered light is at the first order proportional to the number of scat-
terers, it becomes proportional to the square of this number if scattering is coherent and if the phase lag between two scattered waves received by the observer is small. If the particles are randomly distributed, this happens in the complete forward direction only (Zagury, 2001b; Bohren & Huffman, 1983).

Coherent scattering will then occur if the particles are identical, if they can consider the source-star as a point source (Crawford, 1968), and if the length difference between the star-observer distance and the path one scattered photon follows is small compared to the wavelength.

The two latter conditions have the following mathematic expression:

\[ \theta \ll 3 \times 10^{-12} \left( \frac{\lambda}{2000 \text{ Å}} \right) \left( \frac{10 \phi_S}{\phi} \right) \left( \frac{d_0}{l_0} \right) \]  

\[ \theta \ll 5 \times 10^{-8} \left( \frac{\lambda}{2000 \text{ Å}} \right)^{0.5} \left( \frac{100 \text{ pc}}{l_0} \right)^{0.5} \left( \frac{d_0}{D} \right)^{0.5} \]  

\( l_0 \) is the observer-cloud distance, \( d_0 \) the star-cloud distance, \( D \) the star-observer distance (\( D = d_0 + l_0 \)), \( \phi \) and \( \phi_S = 1.4 \times 10^6 \text{ km} \) the diameters of the star and of the sun, \( \theta \) the angular distance viewed from the observer within which scattering is coherent.

In Zagury (2000b) I made a mistake. I have neglected condition 1 which in most cases is the constraining one. We can estimate a typical order of magnitude of 12" for the angular distance from the star within which scattered starlight is coherent. For a cloud at 100 pc this represents \( \sim 10^6 \text{ cm}^2 \) (\( \sim 100 \text{ m}^2 \)). If \( \beta \) is the proportion of scatterers relative to the number of hydrogen atoms, for a typical \( N_H = 10^{20} \text{ H/cm}^2 \) column density, coherent scattered light is \( \beta 10^{26} \) times what it would be if scattering was incoherent.

6 Consequences and prospectives

6.1 Nature of the scatterers

Thierry Lehner, from the Observatoire de Meudon, suggested to me that the scatterers could be atoms or molecules from the gas. This hypothesis is attractive both because the gas is the principal component of interstellar clouds and because it ensures that the scatterers are identical. According to Rayleigh (1871), a set of atoms or molecules will diffuse as \( \lambda^{-4} e^{\alpha \lambda^{-4}} \) (\( \alpha \) a constant proportional to the number of particles). This expression will be consistent with the observations if \( \alpha \lambda^{-4} \) is negligible in the UV. Diffusion by atomic or molec-
ular hydrogen, because of the symmetry of the particle, may introduce a $\lambda^{-6}$ term (in addition to the $\lambda^{-4}$ one) in the scattering cross section (see Jackson (1975)).

According to Sellgren (1983) small grains are necessary to explain the infrared spectrum of interstellar clouds. These grains, if they exist, can also do the coherent scattering.

6.2 Column density of scatterers

To estimate the column density of scatterers (in the cases of hydrogen and of small grains in the following) we need the scattering cross section $\sigma$, which depends on wavelength.

A 15% ratio between scattered light and direct starlight corrected for extinction, corresponds to a column density $N$ of scatterers:

$$ N \sim 1.2 \frac{d_0}{l_0 D} \sigma^{-0.5} \theta^{-2}$$  \hspace{1cm} (3)

Relation 1 then implies:

$$ N \gg 1.7 \times 10^{13} \frac{l_0}{D} \frac{100 \text{ pc}}{d_0} \left( \frac{\Phi}{10 \Phi_S} \right)^2 \sigma_0^{-0.5} \quad (4)$$

with $\sigma_0 = \sigma(\lambda/2000 \text{ Å})^2$.

The scattering cross section of hydrogen for Rayleigh scattering is calculated from the polarisability: $\sigma_0 = 2.3 \times 10^{-4} \text{ cm}^2$.

For small spherical grains: $\sigma_0 = 3.2 \times 10^{-8}(a/100 \text{ nm})^6 \text{ cm}^2$ (Van de Hulst (1969), section 6.4). $a$ is the size of the particles.

Thus, respectively for hydrogen and for small grains:

$$ N_H \gg 10^{27} \text{ cm}^{-2} \frac{l_0}{D} \frac{100 \text{ pc}}{d_0} \left( \frac{\Phi}{10 \Phi_S} \right)^2 \quad (5)$$

$$ N_{\text{grains}} \gg 10^{17} \text{ cm}^{-2} \frac{l_0}{d_0} \left( \frac{\Phi}{10 \Phi_S} \right)^2 \left( \frac{100 \text{ nm}}{a} \right)^3 \quad (6)$$

These calculations are given for sake of completeness. I do not have the practice of diffusion experiments which is necessary to judge of their validity. Should they be correct, coherent scattering by hydrogen is to be ruled out.
6.3 Analytic fit of the extinction curve

‘Donnez-moi quatre paramètres et je vous dessine un éléphant; donnez m’en un cinquième et il aura une trompe.’ citation attribuée à Joseph Bertrand, mathématicien français (1822-1900)

The traditional fit of the extinction curve by Fitzpatrick & Massa (1990) requires five to six parameters (three for the bump region). Fitzpatrick & Massa (1990) decomposition is a purely mathematical approximation with no physical meaning at all. Except for maybe the bump region, if the bump truly is absorption by some specific type of grain. The validity domain of the Fitzpatrick & Massa fit is restricted to the UV: I have checked on some examples that the extension of the fit to the visible often diverges from what is observed. What predictive value can we give to a fit which is limited to the UV domain it was made for? Is it a surprise if, using this fit, no relation was found between the three parts the standard theory distinguishes in the extinction curve, between the visible and the far-UV in particular?

The separation of the extinction curve in direct starlight and scattered light, the fit of each of these parts by the corresponding mathematic expression, the relation between visible and far-UV extinctions (section 3), prove that it is possible to give a physical meaning to the fit of the extinction curve, and to diminish the number of parameters necessary to fit the curve (Zagury, 2001a).

I believe a study of the variations of the extinction curve (in the visible and in the UV) for a large sample of stars observed behind one cloud will bring a better understanding of the extinction curve and will permit to fix its’ exact number of free parameters.

6.4 The 2200 Å bump

The comparative study of different observations recalled in the first sections of this paper casts new light on the near-UV part and the far-UV rise of the extinction curve. The usual explanation of the bump, as a classical extinction process, can apply to this new context. But, as it is mentionned in Zagury (2002b), it is not obvious that this is the case.

Both in the fit found for HD46223 (figure 1), and in Seaton’s curve (figure 1 in Zagury (2002b)), the extinction of the direct starlight approximately passes by the extremum of the bump. Thus, the possibility for the bump to be an interruption of the scattered light only, and not of the direct starlight, can not be neglected.

Here again observations of many stars behind a cloud may be the way to
understand how the bump is created.

7 Conclusion

The standard interpretation of the extinction curve was established from a phenomenological and straightforward reading of its’ different parts. The efforts developped to give a physical support to this interpretation led to sophisticated, but never satisfying, interstellar dust models. In Zagury (2002b) I have used arguments of common sense to prove that this rushed reading of the extinction curve is not in agreement with the observation. I present that the only alternative to the standard interpretation, namely that the spectrum of a reddened star is contaminated by scattered light, logically solves the main problems the extinction curve poses: its’ interpretation, the relation between its’ mathematical representation and physics.

The light we receive from a reddened star is contaminated by scattered light. The intensity of the scattered starlight is important if the scattered waves are coherently added. The angular distance from a reddened star, as seen by the observer, within which scattering is coherent, is small, of order $10^{-12}\text{''}$ from the star. For sufficient reddening the far-UV scattered starlight is much larger than the direct starlight: in this case the far-UV light we receive from the direction of the star is nearly all scattered light, the star is not directly observed (it is totally extinguished).

The exact extinction curve of starlight by dust grains is a straight line from the near-infrared to the far-UV.

The comparison between the UV scattering law in the nebulae and the law found for the scattered light which contaminates the spectrum of reddened stars shows that two kind of particles are necessary to explain the extinction of starlight. Large grains, with a forward scattering phase function and an extinction cross-section $\propto 1/\lambda$; and small particles (atoms, molecules or dust), which diffuse according to Rayleigh’s law, with a near-isotropic phase function and a scattering cross-section $\propto 1/\lambda^4$.

In this context, there is no more reason to suppose there are variations of the average properties of interstellar dust from one region to another.

Several questions are still open. The most important ones are the nature of the 2200Å bump, the exact number of degrees of freedom the extinction curve has, and the nature of the scatterers. The 2200Å bump may not be a classical extinction process by some kind of dust grain. Only the scattered starlight seems to be extinguished in the bump region, leaving the direct starlight un-
affected. The degrees of freedom of the extinction curve (6 in the Fitzpatrick & Massa (1990) decomposition) are already diminished. I believe that a study of the extinction curve, if it can be established for a large set of stars, observed behind the same cloud, in the optical and in the UV, will permit the understanding of the origin of the bump, and constrain the number of free parameters in the extinction curve.

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Fig. 1. The reduced spectrum of HD46223 and its decomposition, outside the bump region into direct starlight and scattered light. The plain curve is the sum of the two components.