Is there ERE in bright nebulae?

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January, 2000

Abstract. In 1986 Witt & Schild studied the optical emission of selected bright nebulae. Comparison of the data to a model led the authors to conclude the nebulae have too high a level of $I$-band emission to be explained solely by the scattering of starlight. The excess is explained as a broad band $I$ emission which originates in the nebulae. This phenomenon is known as Extended Red Emission (ERE).

Given Witt & Schild’s data, the model they employed, and the estimate of observational errors, I’ve reached a different conclusion: Witt & Schild’s observations are compatible with classical scattering and therefore cannot be used to prove the existence of ERE.

Key words: reflection nebulae, ERE

1. Introduction

In 1986, Witt and Schild (1986, WS hereafter) presented CCD photometric observations of 15 nebulae, amongst which are the brightest nebulae of the Galaxy, all illuminated by close B stars.

The data set assembled by WS is of great interest since it fosters better understanding of the properties of interstellar grains and of the structure of the nebulae. The dependence of the surface brightness of a nebula with distance to the star, the estimate of the surface brightness per unit radiation field, and the color of the nebulae, narrow the search for better knowledge of grain properties and will indicate whether or not scattering alone accounts for all nebulae emission.

The surface brightness at wavelength $\lambda$, $S_\lambda$, of a nebula assumed to scatter the light of a nearby star is proportional to the starlight flux $F_\lambda^1$ at the cloud location. We have no direct way of knowing $F_\lambda^1$ but the ratio $S_{\lambda_1}/S_{\lambda_2}$ of two optical bands is proportional
to $F_{\lambda_1}^0/F_{\lambda_2}^0$, $F_{\lambda}^0$ being the flux of the star measured on earth and corrected for reddening. $S_{\lambda}$ is an observational value and $F_{\lambda}^0$ can be estimated from the observed flux of the illuminating star and the extinction $A_V$ in the direction of the star.

$$\Delta C^0(\lambda_1, \lambda_2) = \log(S_{\lambda_1}/S_{\lambda_2} \times F_{\lambda_2}^0/F_{\lambda_1}^0)$$ can be known with sufficient accuracy to be compared to simple models, such as the ones proposed by Witt (1985) or by Zagury, Boulanger and Banchet (1999). $\Delta C^0(\lambda_1, \lambda_2)$ depends exclusively on the optical depth of the scattering medium and on the properties of the grains. It may also depend on the structure of the medium if regions of different optical depths are mixed in the beam of the observation.

The WS paper compares the colors $\Delta C^0(B, V)$ and $\Delta C^0(V, I)$ of the nebulae to the model proposed in Witt (1985). The conclusion is summarized by figure 14 of WS’ paper, which is reproduced here (figure 1). WS attribute the difference between the model and the observations to a non-scattering emission process in the $I$ band. This Extended Red Emission (ERE) is presumed to be luminescence from a particular type of interstellar grain.

Before agreeing with WS’ conclusion different questions must be clarified.

Why do most of the observational points of the WS figure 14 follow a curve which is parallel to the model?

How does the reddening of the stars affect $\Delta C^0$ and modify the relative positions of the observation values and the model on the color-color plot?

According to Witt (1985), no model can be perfect, and models of reflection nebulae usually meet with only limited success. The Witt model, which represents nebulae as homogenous gas masses of defined geometry, may incorrectly represent the nebulae. Will small scale structure, for instance, modify the color forecast of an observation from the one predicted for a homogenous nebula? Are the limits of the model consistent with the high column densities which likely prevail in the nebulae?

How do observational and data reduction errors influence WS’ conclusion? Variations of surface brightness with angular distance $\theta$ to the star, which roughly follows a $\theta^{-2}$ will be used to prove the abnormal behaviors of the I surface brightness of some nebulae. A major, and extremely difficult to correct, source of error is the gradient due to starlight diffusion in the earth’s atmosphere which usually accompanies observations of nebulae at close distances to a bright star (see Zagury, Boulanger and Banchet, 1999).

Attempts to answer these questions will be found in the following sections. In section 2, WS data and argumentation are reviewed. In section 3, $\Delta C^0(B, V)$ and $\Delta C^0(V, I)$ are extracted from the data and compared to the Witt model. The influences of column densities higher than permitted by the low column density approximation of the Witt
Fig. 1. left: WS figure 15, $\Delta C(B, V)$ versus $\Delta C(V, I)$. The line drawn corresponds to $\Delta C^0(B, V)$ versus $\Delta C^0(V, I)$ for a homogenous mass of gas of varying optical depth, computed in the approximation of single scattering. right: observed $\Delta C^0(B, V)$ versus $\Delta C^0(V, I)$. Calculated from $E(B - V)$ given in WS. This plot does not figure in WS.

2. Data and WS interpretation

For 3 to 25 chosen positions in each field, WS give the distance to the star, $d_\theta$, and $\log(S_\lambda/F_\lambda^\star)$, where $S_\lambda$ and $F_\lambda^\star$ are the nebula surface brightness and the star flux (not corrected for reddening), measured on earth, in the $V$, $B$, $R$, $I$ bands. Because of the proximity of the star (positions are between 20” to 150” to the star), WS had to subtract a gradient due to starlight scattering in the earth’s atmosphere.

I used WS data to reproduce their figure 15 (figure 1 left). The plot is $\Delta C(V, I)$ versus $\Delta C(B, V)$ with $\Delta C(\lambda_1, \lambda_2) = \log(S_{\lambda_1}/F_{\lambda_1}^\star) - \log(S_{\lambda_2}/F_{\lambda_2}^\star)$.

The plain line in the plot is the variation with optical depth of $\Delta C(V, I)$ and $\Delta C(B, V)$, and assumes no reddening of the illuminating star. It was calculated from the model described in Zagury et al. (1999) whose application is restricted to single scattering and is in agreement with the Witt model. Both models assume the star and the nebula...
to be equally reddened by forward material -if any. Witt’s model (see the equation 2 of Witt 1985) approximates the scattered part of the extincted light by $g(\varphi)\omega(1 - e^{-\tau})$ where $\omega$ is the albedo of dust grains, $g$ the phase function, $\varphi$ the angle of scattering, and $\tau$ the optical depth of the medium. The model applies to small optical depth mediums where single scattering dominates.

Most of the observed points are below the model line, which WS interpret as $I$ values too large to be the result of scattering. They conclude that ERE accounts for 30% to 50% of the $I$ band surface brightness.

3. Discussion

3.1. Correction for the extinction of the stars

I will introduce:

$$\Delta C^0(\lambda_1, \lambda_2) = \log(S_{\lambda_1}/F_{\lambda_1}) - \log(S_{\lambda_2}/F_{\lambda_2})$$

(1)

$F_\lambda$ is the star flux at wavelength $\lambda$, measured on earth and corrected for reddening.

$\Delta C^0$ so defined is a possible definition for the color of a nebula. A significant difference exists between the traditional meaning of color and $\Delta C^0$: when increasing the optical depth of a low density medium, $B - V$, $B - I$ and $V - I$ colors increase while $\Delta C^0(B, V)$, $\Delta C^0(B, I)$, $\Delta C^0(V, I)$ decrease.

$\Delta C^0(V, I)$ and $\Delta C^0(B, V)$ anticipated values for a medium with little reddening are $\Delta C^0(V, I)_{\text{max}} = 0.34$ and $\Delta C^0(B, V)_{\text{max}} = 0.13$ ($A_B/A_V = 1.34$ and $A_I/A_V = 0.45$, Cardelli et al. 1989). Extinction effects in mediums with increasing optical depths can only decrease (reden) $\Delta C^0(V, I)$ and $\Delta C^0(B, V)$, so that one should always have: $\Delta C^0(V, I) < \Delta C^0(V, I)_{\text{max}}$, and $\Delta C^0(B, V) < \Delta C^0(B, V)_{\text{max}}$, if scattering alone is considered.

The model curve of figure 3 is the theoretical color-color plot ($\Delta C^0(V, I)$, $\Delta C^0(B, V)$) for a medium of low optical depth. The model assumes that starlight is not reddened between the star and the nebula. Starlight extinction between the star and the scattering volume will redden the visible emission of the nebula and move the model curve down and to the left, thus approaching the observations.

$\Delta C^0(V, I)$ and $\Delta C^0(B, V)$ can be estimated from $\Delta C(V, I)$ and $\Delta C(B, I)$ in the following manner. At optical wavelengths, $A_\lambda$ is a linear function of $1/\lambda$ (Cardelli, Clayton & Mathis 1989, Rieke & Lebofsky 1985). Hence:

$$A_{\lambda_1} - A_{\lambda_2} = \frac{E(B - V)}{\lambda_2 - \lambda_1} \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

$$= 2.2E(B - V) \left(\frac{1\mu m}{\lambda_1} - \frac{1\mu m}{\lambda_2}\right)$$

(2)
Use of relation 2 in the definition of $\Delta C^0$ gives:

$$
\Delta C^0(\lambda_1, \lambda_2) = \Delta C(\lambda_1, \lambda_2) - 0.9 E(B - V) \left( \frac{1 \mu m}{\lambda_1} - \frac{1 \mu m}{\lambda_2} \right) 
$$

(3)

$$
\Delta C^0(B, V) = \Delta C(B, V) - 0.4 E(B - V) 
$$

(4)

$$
\Delta C^0(V, I) = \Delta C(V, I) - 0.6 E(B - V) 
$$

(5)

Figure 1, left, plots the observed values of $\Delta C(V, I)$ and $\Delta C(B, I)$ for the nebulae WS have considered. Most points follow a curve parallel to the model curve but shifted down from it.

A few points, mainly observations of NGC2068, have $\Delta C(V, I)$ greater than $\Delta C^0(V, I)_{max}$. Roughly half of $\Delta C(B, V)$ values of the plot are significantly above 0.13 mag. This is to be attributed to the reddening of the stars which decreases $\Delta C^0(B, V)$ and $\Delta C^0(V, I)$ according to equations 3 and 4. Correction for the reddening of the stars will shift all the observations down by 0.6$E(B - V)$ mag and to the left by 0.4$E(B - V)$ mag. $E(B - V)$ is given in table 1 of WS.

The color-color diagram ($\Delta C^0(V, I), \Delta C^0(V, I)$) is represented on the right hand plot of figure 1. Most nebulae observations are now scattered close to the model curve.

Different reasons may explain departures from the model line and the tendency for the nebulae to remain under the curve. Error bars explain part of the difference between the model and the observations. The Witt model is restricted to low column densities since it requires single scattering and low optical depth. What is the effect of an increase of column density? The nebulae of the Witt model must be homogenous enough for the medium sampled by the beam of the observation to be described by one value of the optical depth ($\tau_0$ in Witt’s model). How will small scale structure modify WS’ conclusions?

3.2. The limits of the Witt model

The limit of validity of the model curve (figure 1) is that single scattering dominates for each of the optical bands. It is satisfied if the scattering volumes are proven to be homogenous (can be described by a single optical depth) and have a low $A_V$ value. According to Witt (1985) the model is valid for $A_V \sim \tau < \tau_{lim} = 0.6$. Since this condition must be satisfied for all the optical bands, it implies: $A_V \sim \tau_V < 0.6$, hence $A_I \sim 0.5 A_V < 0.3$.

WS’ representation of the medium surrounding the stars (§ III b in WS), by a homogenous spherical nebula of radial optical depth $A_V \sim 0.5$ mag, is within the limits of the single scattering model but is questionable. The selection criteria of nebulae with high surface brightnesses in largely extincted regions, some of which are starforming regions,
supports the idea of high column densities and perhaps a wide range of structures with different optical depths along each line of sight.

High column densities in the nebulae are also indicated by the extinction in the direction of the stars. $A_V$ in the stars direction should be the radial optical depth to use in the Witt model. Nearly all the stars in the sample have large reddening, $E(B-V)$ for all stars except one, the illuminating star of IC426, is greater than 0.2, with a mean value $\sim 0.7$ (WS, table 1). With a minimum $R_V = A_V/E(B-V)$ of 3 (Cardelli et al. 1989), the $A_V = 1.08\tau_*$ value found for the nebulae will range from 0.6 to 4.2, with an average value of 2, far above $\tau_{lim}$ and above the radial optical depths adopted in WS.

Observations do not agree with WS’ concept of the nebulae. Column densities must be higher than $A_V = 0.5$. The effect on the color-color plot of such high column densities, out of the range of validity of the single scattering model, is investigated in section 3.3.

A clumpy medium made of cells of different column densities, and much smaller than the resolution of the observations, may be an alternative representation of the homogenous mass of gas adopted in WS. It will modify (section 3.4) the color of the nebulae and can explain the high surface brightnesses observed in all the optical bands.

### 3.3. Effect of an increase of the column density on the model curve

If the column density of the medium which is observed is increased, the single scattering approximation will stop being valid in the $B$ and in the $V$ bands before the $I$ band. At low column density ($A_V \ll 1$), scattering in the $I$ band will be $\sim 3$ times less (Cardelli et al. 1989) than in the $B$ band. Increasing the column density will see the domination of absorption effects in the $B$ band while scattering in the $I$ band will become important. For $A_V \sim 3$, we have $A_I \sim 1.35$ and $A_B \sim 4$. Given these values, scattering will be minimal in the $V$ and $B$ bands, most of the $B$ and $V$ light will be absorbed. It is close to its maximum in the $I$ band. $B$ and $V$ surface brightnesses will be close to 0 and $I$ surface brightness close to its maximum.

Hence, the net effect of an increase of column density will be to shift the model points of figure 1 down, as observed. The points are also shifted to the left, but the effect is less important (section 3.1, equations 4 and 5).

The model curve of figure 1 is a limit which separates two regions. All observations should lie in the region under the curve. The few points above the model curve will be explained by the error margin of the observations.

### 3.4. Effect of the small scale structure

The ambiguity between the high column densities which exist in the nebulae and the observed high surface brightnesses in all bands can be removed if the emission in the
Fig. 2. Plot of $\log(S_\lambda/F_\lambda)$ versus distance to the illuminating star for the $B$, $V$, $R$, $I$ bands and for 3 nebulae. The $I$ band values of IC435 (left plot, asterix) are nearly constant and do not follow the variations of the other band, as in most other fields. A plausible interpretation is the gradient subtracted from $S_\lambda$, which may introduce a variable offset.

Various bands is not exactly produced by the same interstellar regions on the same line of sight. High $I$ band surface brightness arises from regions with relatively high optical depth ($A_V > 1$) which will absorb $V$ and $B$ starlight and produce little emission in those bands. The $B$ and $V$ band emissions should come from regions of the same line of sight, with lower $A_V$, as in the WS model. Those regions will give little scattering in the $I$ band. If this is the case, one cannot expect the observations to match the uniform mass of gas model.

The contribution of structures with high $A_V$ to the emission in the $I$-band will contribute to the drop in $\Delta C^0(V,I)$ observed for some points in the right plot of figure 1.

The probability that the observed nebulae are structured at small scales is strengthened by the beam size of WS observations. WS images’ resolution is not better than 10” and the average distance to the nebulae is, according to WS’ table I, $600 \pm 300$ pc. Thus, the spatial resolution of the observations is at least 0.03 pc, a large value (3 orders of magnitude) compared to the possible interstellar clouds scale ($\sim$ a few tens of A.U., Falgarone et al. [1998], Zagury et al. [1999]).

3.5. Error bars

Most observations (figure [1], right) lie under the model line and at close distance to it, which can be justified either by higher column densities than permitted by the model or
by the small scale structure of the medium. Error bars will explain the extreme position on the plot of some observations.

The uncertainty of $E(B-V)$ introduces an error on $\Delta C^0(B,V)$ and on $\Delta C^0(V,I)$. The error on $E(B-V)$ is probably less than 0.1 and may produce a similar error in $\Delta C^0(B,V)$ and $\Delta C^0(V,I)$.

Error bars on the observed values, $\Delta C(B,V)$ and $\Delta C(V,I)$, may be larger than WS estimates due to the atmospheric gradient substracted from each observation. The same problem was dealt with in Zagury et al. (1999): a precise subtraction of the atmospheric gradient was found to be impossible to arrive at.

3.5.1. NGC1333 and NGC2247

The singular positions above the model line of NGC1333 and of some of NGC2247 observations must be due to an error in the data. For NGC2247, the error, given in WS, $\sim \pm 0.04$ to $\pm 0.12$ for $\Delta C(B,V)$ and $\Delta C(V,I)$, is enough to bring all points back under the model line.

Errors given for NGC1333 are lower, of order $\pm 0.04$, and may have been slightly underestimated. Along with a possible overestimation of the $E(B-V)$ value of BD+30$^\circ$549, the illuminating star of NGC1333, error bars also explain the extreme positions of NGC1333 observations in the right plot of figure 1.

3.5.2. IC435, NGC2245 and NGC6914a

Three nebulae, IC435, NGC2245, NGC6914a are far under the model curve. Some of these points have $\Delta C^0(B,V) > \Delta C^0(B,V)_{max}$ which must indicate error bars larger than WS’ estimates.

Figure 2 displays $\log(S_\lambda/F_\lambda)$ versus $\log d_\theta$ for some stars. For most nebulae the surface brightness decreases when moving away from the star, in all the optical bands. The decrease follows a $1/d_\theta^2$ law for the fields NGC1788, IC446, NGC2247, NGC2327, NGC7023, and Ced201 (figure 2, right plot). Similar variations of $\log(S_\lambda/F_\lambda)$ versus $\log d_\theta$ are observed in most fields and all optical bands. Important differences also arise, especially in the $I$ band.

A particularly neat example is IC435 where $B, V, R$ surface brightnesses decrease as $1/d_\theta^2$, while $I$ surface brightness remains constant (figure 2 left plot). $\log(S_\lambda/F_\lambda)$ values for IC435 are nearly equal in the $B, V, R$ bands (figure 2) at all positions. The peculiar behaviour of IC435 in the $I$-band (figure 2, left) is most probably explained by a large error in $I$ surface brightness. The error on $\Delta C(B,V)$ and $\Delta C(V,I)$ for IC435, estimated by WS, is of order $\pm 0.1$. An error of $\pm 0.2$ to $\pm 0.3$ seems to be more likely for $\Delta C(V,I)$. 


Like IC435, the $I$-band variations (not represented here) of NGC2245 and NGC6914a do not follow the $B$, $V$, and $R$ band variations. Errors for these two stars, given in WS, are substantially higher than for IC435. They reach 0.2, a value comparable to the one inferred for IC435.

4. Conclusion

In this paper I tried to show that WS analysis of the emission of bright nebulae is not conclusive. The observations are compatible with starlight scattering as the only process involved.

The first part of WS’ paper is dedicated to the comparison of the color of the nebulae with Witt’s model, which applies to low column density nebulae where single scattering in all optical bands dominates. The curve which represents this model in a $(\Delta C^0(B, V), \Delta C^0(V, I))$ plot is to be considered as a limit under which all observations should be.

Correction for the reddening of the stars will scatter most observations close to the model line, where they have a tendency to remain under the line, as expected.

Three reasons explain the remaining differences between the model and the observations.

A deeper analysis of the error margin of the observations explains the largest differences between the Witt model and WS’ observations. The main source of error is the gradient of starlight scattered in the earth’s atmosphere which needs to be subtracted from the observations.

The general drop of the observations under the model curve can be attributed to column densities higher than tolerated by the single scattering model. Fitting the observations to the model in the $B$ or the $V$ band, as is done in WS, will give low $A_I$ and low $I$ surface brightness values for the nebulae, incongruous with the large reddening of the stars. The $A_V$ values in the direction of the stars are between 1 and 4, with a mean value of 2, above the maximum optical depth ($\sim 0.6$) supported by the model.

High surface brightness in the I-band does not prove ERE, but indicates optical depths in the $B$ and $V$ bands higher than can be supported by the model. The expected position of these observations on the color-color plot will be under the curve, as it is observed.

The small scale structure of the nebulae will also heighten differences between the Witt model and the observations. A structured medium permits high surface brightnesses in all bands since the bulk of the emission at two different wavelengths need not arise from the same interstellar structures. Small scale structure in the sample of nebulae presented in WS is probable because of the large beam of the observations and the high column densities in the nebulae.
The Witt model, which represents the nebulae as spheres of constant density centered on the star, never fits the $V$ band observations variation with distance to the central star. But up to what point is it reasonable to expect the observations to match the model? When the observations do not match the representation of a nebula proposed in WS shouldn’t the model be questioned first, before concluding that interstellar grains have special properties which vary from cloud to cloud?

The many different aspects discussed in this paper indicate that WS’ observations can be explained by scattering effects only. While it certainly is possible to interpret the data with excess of red emission, this interpretation requires a constrained and limited model which is probably a poor representation of reality and whose reliability the authors have yet to prove.

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