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Letter to the Editor

O°(63 μm) line emission in the IRAS 60 μm band

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Abstract. The IRAS 60 and 100 μm flux measurements are commonly explained by dust continuum emission, but this explanation sometimes requires unexpectedly high dust temperatures.

We show that the contribution of fine structure radiation of neutral oxygen, O°(63 μm), can be significant in the IRAS 60 μm band. The O°(63 μm) line emission together with the dust continuum emission offers a plausible explanation of the observed flux ratio $I(60)/I(100)$, as well as of its variation in individual clouds. As an example we discuss the cirrus cloud G230-28N.

Key words: Atomic processes — Infrared radiation — Interstellar medium: clouds: general

1. Introduction

During the IRAS mission it became generally clear that a wide spread emission component was found in the interstellar medium, the now so called 'cirrus clouds' (Low *et al.*, 1984). Isolated cirrus clouds at high galactic latitude ($|b| > 20^{o}$) are good specimens to study, because: (1) there is no blending with other background features; (2) they appear as optically thin clouds: $A_V < 1$ (de Vries and le Poole, 1985); (3) the (galactic) radiation field is well determined (Mathis *et al.*, 1983).

We systematically searched for such isolated clouds on high quality SERC/ESO Schmidt film copies. All the faint 'emission' and extinction features we found show 60 and 100 μm emission. The optical radiation is in fact no true emission but galactic light reflected by dust (Sandage, 1976; de Vries and le Poole, 1985) and is well correlated with the far infrared (FIR) emission seen on IRAS 100 μm maps (de Vries and le Poole, 1986; Leene, 1987; Laureijs, 1989).

The mid infrared (12 and 25 μm) emission is attributed to a group of very small grains (radii ~0.5 nm) (Draine and Anderson, 1985), to large aromatic molecules (Puget *et al.*, 1985) or to partially hydrogenated amorphous hydrocarbons (Duley and Williams, 1988), with heat capacities too small to be in thermal equilibrium with the radiation field.

It is assumed that the FIR 100 μm emission and the scattering at optical wavelengths are caused by a population of big dust particles, that is in thermal equilibrium with the radiation field (Mathis *et al.*, 1983; Walterbos and Schwering, 1987). These classical grains (radii $\sim 0.01 - 0.1\mu$m) should have an equilibrium temperature below 20 K (Spencer and Leung, 1978; Black, 1987; Chlewicki, 1987).

These models have the following problems:
(1) If both the 60 μm and the 100 μm emission of these clouds are caused by only one population of dust particles in thermal equilibrium with the radiation field at temperatures ~ 18 K, we would expect a constant $I(60\ \mu\mathrm{m})/I(100\ \mu\mathrm{m})$ brightness ratio ~ 0.1. However, the observed 60/100 ratio of these clouds is variable from region to region and on average higher by a factor of 2 (Harwit *et al.* 1986, Laureijs *et al.* 1988), requiring grain temperatures of order 24 K.
(2) Detailed analysis of some clouds show an increase of the 60/100 ratio towards the centre of the cloud (Laureijs *et al.*). Thus thermal equilibrium emission of a single type of dust particles cannot explain the FIR emission. As a solution Laureijs *et al.* (1988) introduce a population of small iron particles with an emission spectrum that peaks at 60 μm.

But what about line emission?
Harwit *et al.* (1986) speculate that the IRAS FIR bands could be largely fine structure emission of $O^{\circ}(63\mu\mathrm{m})$ and $O^{2+}(88\mu\mathrm{m})$ in respectively neutral and ionized diffuse clouds. Especially for diffuse clouds, such as these cirrus clouds are, the fine structure lines of C^{+} and O° are expected to be very strong, because the fine structure levels are only a few hundred K above the ground state and lie in the FIR where the general interstellar extinction is low. These lines will determine the cooling of the gas and are thus very important in the energy balance.

We investigate under what conditions the contribution of the O° 63 μm line to the 60 μm IRAS broad band flux is large enough to alleviate the problems mentioned above. As an example we study the properties of the diffuse galactic cloud G230-28N (de Vries and le Poole, 1985; Laureijs *et al.*, 1988).

2. Observations and Data reduction

We used the IRAS database to construct co-add maps of a 2° x 2° field around G230-28N. In this way we achieved better angular resolution than is available in the standard IRAS 'skyflux' images. In summary a co-add map is created as follows (for a more complete description we refer to Schwering, 1988): (1) Select all IRAS Survey scans in the field; (2) create a map for every individual survey scan; (3) combine all survey

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scan maps into a single map in each band (12, 25, 60 and 100 μm); (4) convolve to Gaussian resolutions to compare different wavelength data.

We destriped the maps to a level low enough to analyse the maps. We subtracted the local background radiation by fitting a plane through areas outside the cloud. The resulting resolutions are: 60 μm: $2.0' \times 6.4'$, 100 μm: $3.8' \times 6.4'$. We estimate the zero level brightness uncertainties at 0.2 and 0.5 MJy ster^{-1} respectively. These are constant offsets over the whole cloud. Figure 1 shows the 100 μm map.

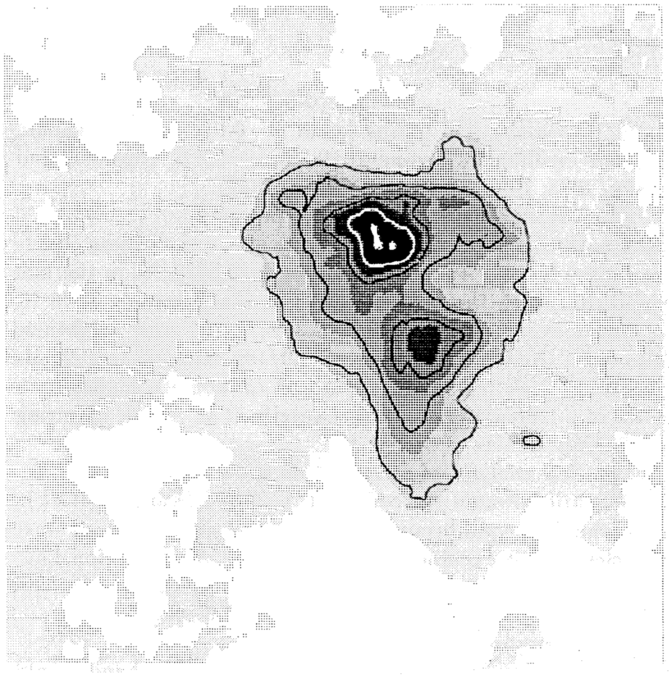

Fig. 1. 100 μm flat-fielded co-add map of a field of 2° x 2° around the cirrus cloud G230-28N. Centred around α : $05^{\rm hr}27^{\rm m}$ δ : $-25°10'$ ($+\alpha$:←, $+\delta$:↑). The angular resolution is: $3.8' \times 6.4'$. Grey scales range from 0-5 MJy ster^{-1}, darker grey scales correspond to higher brightnesses. Contours are at 1, 2, 3, 4, 5 MJy ster^{-1}.

3. Analysis

Under the assumption that all of the 60 μm and the 100 μm emission is produced by the same interstellar dust particles, we made a map of the dust temperature distribution of the cloud. We convolved the 60 μm map to the 100 μm map resolution assuming Gaussian beam shapes. We then determined the intensity ratio for every pixel. Assuming that the dust particles emit as a blackbody with emissivity coefficient $\epsilon_\lambda \sim \lambda^{-1}$ we derive the dust temperature T from:

$$\frac{I(60)}{I(100)} = \left(\frac{100}{60}\right) \frac{B(60\ \mu\mathrm{m}, T)}{B(100\ \mu\mathrm{m}, T)} \qquad (1)$$

Figure 2 shows the resulting temperature map. Darker areas correspond to higher temperatures. The temperature ranges from 22-28 K. Note the nearly constant value of the temperature in the outer parts and the steep rise near the centre of the cloud.

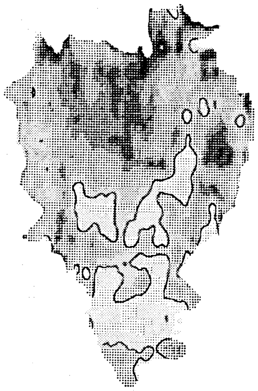

Fig. 2. Temperature map of G230-28N, assuming both 60 and 100 μm emission are caused by continuum emission of the same dust, modelled with a modified Planck spectrum. Grey scales range from 22-28 K, darker grey scales correspond to higher temperatures. The contour is at 25 K.

4. Model presentation

4.1. Introduction

The observed 60/100 ratio for diffuse cirrus clouds cannot be explained by the large dust particles of the two-dust grain model, (a) because these grains should have an equilibrium temperature lower than 20 K (Sect. 1), (b) because a variation of this ratio is unlikely in view of the low optical depth and the uniform radiation field.

Draine and Anderson (1985) showed that temperature fluctuations in a graphite and silicate mixture with size distributions extending to very small sizes ($\sim$ 0.3 nm) can explain a higher brightness ratio: $I(60)/I(100) \sim 0.2$. Chlewicki and Laureijs (1988) showed that the required temperatures can be attained at equilibrium with the radiation field, by introducing *(ad hoc)* a group of small iron particles with a temperature $T \sim 60$ K and radii $\sim$ 7 nm. Both these models produce a higher 60/100 ratio, but only the latter explains the variation of this ratio towards the centre of a cloud (by increasing the absorption coefficient of the iron particles).

4.2. The oxygen 63 μm cooling line

A more attractive explanation of the strength and the variation of $I(60)/I(100)$ is to assume a contribution to the IRAS 60 μm broad band flux by the O°(63 μm) line. In Table 1 we have listed the parameters for the ground triplet of O°.

That such a contribution could be significant is shown by the calculations by van Dishoeck and Black (1988) for the cloud in front of ζ Oph: $I(63\ \mu\mathrm{m}) = 2\times10^{-9}$ W m^{-2} ster^{-1}. Because the IRAS 60 μm band has a width of $\Delta\nu = 2.58\times10^{12}$ Hz, the line thus would contribute 0.08 MJy ster^{-1} to the 60 μm measurement, or 5-30% of the flux density that we find. Harwit *et al.* (1986) expect line fluxes for O° (63 μm) to contribute of order of ~ 0.1 MJy ster^{-1} in the IRAS 60 μm band, based on independent calculations (quoted from the thesis of Stacey) for the total amount of ionized and neutral gas in the Galaxy. These two calculations are in good agreement with each other.

Table 1. Fine structure parameters of O°.

species	transition	E(K)	λ(μm)	A(s^{-1})
O°	$^3P_1 \rightarrow {^3P_2}$	228	63.2	8.95x10^{-5}
	$^3P_0 \rightarrow {^3P_1}$	98	145.5	1.70x10^{-5}
	$^3P_0 \rightarrow {^3P_2}$	326	44.0	1.0 x10^{-10}

Consider an (at 63 μm) optically thin cirrus cloud with densities n_H H°, n_O O° atoms and n_e electrons per cm^{-3} at temperature T and with a thickness d (pc). The intensity of an optically thin O° line can be written by:

$$I = \frac{1}{4\pi} n_H \, n_O \, d \, \{L_H(O,T) + x_e L_e(O,T)\} \tag{2}$$

where L_H and L_e are the cooling efficiencies for collisions of O° with H° and electrons respectively; and $x_e = \frac{n_e}{n_H}$ is the fractional ionization.

From A_V, we determine $n_H d = A_V$x19x10^{20} H-atoms cm^{-2} (Bohlin *et al.*, 1978); for $A_V = 0.4$ (de Vries and le Poole, 1985; Stark *et al.*, 1990), we find $n_H d = 7.6\text{x}10^{20}$. The cooling rates depend exponentially on the gas temperature. For a two level approximation we may write:

$$L_i(O,T) = <\sigma v> E_{21} \, \frac{g_u}{g_l} \, e^{-228/T} \tag{3}$$

where σ is the cross section for deexciation, σv is averaged over a Maxwellian distribution and is usually not a strong function of the temperature. For $T = 100$ K and considering all three levels, we may write: $L_H(O,T) = 1.7\text{x}10^{-25}$ erg cm^{-3} s^{-1} (Launay and Roueff, 1977) and $L_e(O,T) = 9.7\text{x}10^{-25}$ erg cm^{-3} s^{-1} (Berrington, 1988). The oxygen density can be written as: $n_O = [\mathrm{O}]/[\mathrm{H}] \, \delta_O \, n_H$, where [O]/[H] = 8.3x10^{-4} (van Dishoeck and Black, 1988) and δ_O is the depletion factor. We will assume $n_H = 270$ cm^{-3}, $x_e = 0$ and $\delta_O = 1$ (no depletion). The contribution of the line to the IRAS 60 μm band then is: ~ 0.1 MJy ster^{-1}. In Table 2 we have listed, as a function of the temperature, the values of $n_H \, n_O \, d$ for a fractional ionization of 0 and 1 %, corresponding to a brightness of 0.1 MJy ster^{-1}. We also list the density n_H, assuming a thickness $d = 1$ pc.

Table 2. Values of $n_H n_O d$ as function of the gas temperature T and a fractional ionization x_e of 0 and 0.01 corresponding to a brightness of 0.1 MJy ster^{-1} of the O°(63 μm) line in the IRAS 60 μm band.

	$x_e = 0$		$x_e = 0.01$	
T (K)	$n_H n_O d$ (cm^{-6}pc)	n_H (cm^{-3})	$n_H n_O d$ (cm^{-6}pc)	n_H (cm^{-3})
200	11	115	11	115
100	60	270	58	265
80	123	385	116	375
50	796	980	747	950

We now write:

$$\frac{I(60\ \mu\mathrm{m})}{I(100\ \mu\mathrm{m})} = \frac{I_{dust}(60\ \mu\mathrm{m}) + I_{O^\circ}(63\ \mu\mathrm{m})}{I_{dust}(100\ \mu\mathrm{m})} \tag{4}$$

The observed value of this ratio is 0.15-0.3 (Laureijs, 1989). If we assume that the dust particles radiating at 60 and 100 μm do have an equilibrium temperature of 18 K , we may write $I_{dust}(60\ \mu\mathrm{m})/I_{dust}(100\ \mu\mathrm{m}) = 0.1$, and we then find from (4):

$$I_{O^\circ}(63\ \mu\mathrm{m})/I_{dust}(100\ \mu\mathrm{m}) = \text{constant} = 0.1 \tag{5}$$

This is indeed observed for G230-28N for $I_{dust}(100) < 2.5$ MJy ster^{-1} and is reflected in Fig. 2 as the outer regions of nearly constant 'temperature'.

4.3. Discussion

The O°(63 μm) intensity is very sensitive to the gas temperature, because of its strong exponential decrease for $T < \frac{E_{ul}}{2}$ (see Eq.(3) and Table 2) and to the degree of ionization, because the cross section for collisions between O° end e$^-$ are so much larger than for O° and H°. The assumed gas temperature: $T = 100$ K, is somewhat higher than the temperatures found in H° absorption studies (Kalberla *et al.*, 1985), who found $< T > \sim 30 - 70$ K. But this does not exclude that in a cirrus cloud most of the hydrogen has a temperature as high as 100 K, because Kalberla *et al.* conclude that only cold clumps are seen in absorption and that they observe only ~ 20 % of the gas that is in emission.

The fact that (cirrus-) clouds at high galactic latitude could be partially ionized is shown by Mathis (1986), who pointed out that 10% of the ionizing photons produced by O stars can penetrate to fair distances above the galactic plane. The measurements by the Reynolds group (e.g. Reynolds, 1985) confirm Mathis conclusion. However, Table 2 shows that even for a fractional ionization as large as 1%, the contribution of electron collisions to the O°(63 μm) line intensity is very small.

A brightness contribution of 0.1 MJy ster^{-1} can easily be obtained for a H° temperature of 100 K. But how can we explain the high ratio $I_{O^\circ}(63\ \mu\mathrm{m})/I_{dust}(100\ \mu\mathrm{m}) \sim 0.14$ at the centre of the cloud? A possible explanation is the following: The gas temperature remains constant, and $n_H n_O d$ gains a factor 7, e.g. $n_H d$ increases a factor 3 and likewise does the density. The increase of $n_H d$ is in agreement with the increase of A_V found from photometry on background stars (Stark *et al.*, 1990). This explanation assumes that T remains constant, a property that is not present in single cloud models (e.g. van Dishoeck and Black, 1988), where we would expect the opposite effect: an increase of A_V (thus an increase of the H° density) causes a shielding of the radiation. As a result the temperature will decrease. The O° density will also decrease because of more depletion on grains. However, a single cloud model may not be the correct one. If the cloud has a clumpy or filamentary structure, an increase of A_V results in a larger surface to volume ratio compared to a single homogeneous cloud (Stutzki *et al.*, 1988). Then the cloud as a whole is penetrated by the radiation field. As a result the O° line intensity increases with A_V. If small density enhancements are present within the filaments, then a reduction of d is also sufficient to get enough I_O emission, even in areas of constant A_V. Because n_H and n_O go up by the same factor while the column density remains constant. Indications for a filamentary and clumpy structure come from digitized optical plates, which have a resolution $\sim 22'' \mathrm{x} 22''$ (Stark *et al.*, 1990).

We recently detected CO(J=1-0) emission with the KOSMA telescope in the centre of the cloud. We find find for the integrated antenna temperature: $I_{CO} \sim 0.8$ K km s^{-1}. If the relations derived by Crawford *et al.* (1985) for the CO and C$^+$ intensity in galaxies are also valid for our cloud, we find for the C$^+$ intensity: $I_{C+} \sim 1\ 10^{-5}$ erg cm^{-2} s^{-1} ster^{-1}. This is nearly the same value we find for the I_{O^o} intensity in the centre! This indicates that the O°(63 μm) and the C$^+$(158 μm) may be of equal importance in the energy balance for diffuse clouds.

The photometric results and the CO data will be discussed in detail by Stark *et al.* (1990).

5. Conclusions

We showed that the O° line *may* contribute significantly in the IRAS 60 μm band with a brightness of: 0.1-0.7 MJy ster^{-1}. This would explain the observed high 60/100 ratio and its variation in individual clouds. This assumption also eliminates the postulated existence of (dust) particles radiating mainly at 60 μm .

In disks of spiral galaxies, the O abundance is decreasing with increasing distance from the centre (Pagel and Edmunds, 1981). We thus expect a decrease of the 60/100 brightness ratio. This is in agreement with the observations of Walterbos and Schwering (1987) for M31 and Deul (1988) for M33. Buat and Deharveng (1988) modelled the 60 and 100 μm emission in galaxies by a cool and warm dust component. They assume that the cool dust contributes $0.2I(100\ \mu\mathrm{m})$ to the 60 μm band, the rest of the 60 μm emission is ascribed to warm dust correlated with the presence of H_α. However, their model can only explain $\sim$ 75% of the 60 μm emission.

Since the atmosphere is opaque at wavelengths around 100 μm, no direct measurements of the O° fine structure lines can be made from the ground. The Kuiper Airborne Observatory can be used, if the line intensities are strong enough. Last but not least, the long wavelength spectrometer on board the ISO satellite will be capable to measure the O°(63 μm) as well as the O°(146 μm) line directly.

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