DIFFUSE MOLECULAR CLOUDS
AT HIGH GALACTIC LATITUDE

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Abstract. The IRAS 60 and 100 μm flux from cirrus clouds are commonly explained by dust continuum emission. But this explanation in some cases requires unexpectedly high dust temperatures.

We argue that the contribution of fine structure emission 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 across individual clouds. We also discuss the clumpy/filamentary structure of these clouds.

Keywords : Atomic processes; Infrared radiation; Interstellar medium : clouds : cirrus

1. Introduction

The IRAS mission revealed a wide spread emission component in the interstellar medium, the now so-called cirrus clouds (Low *et al.*[1]). Most of the cirrus clouds appear as optically thin clouds : A_V <1 mag (e.g. de Vries and le Poole[2]). Because their distance from the Sun is of the order 100 pc (Magnani and de Vries[3]), cirrus clouds can be studied in great detail. The best way to study their nature is to look for isolated cirrus clouds at high galactic latitude, where : (1) the geometry of the dominant radiation field is known (i.e., the general galactic radiation field), (2) there is no blending with possible background features.

The IRAS 100 μm brightness of cirrus is very well correlated with the visual extinction seen at optical wavelengths[2,3]. It is generally assumed that both phenomena are caused by one population of big (radii of order of 0.01-0.1 μm) dust particles, which are in thermodynamic equilibrium with the radiation field (Mathis *et al.*[4]). These dust particles should have an equilibrium temperature below 20 K (Spencer and Leung[5], Black[6]; Chlewicki[7]).

Figure 1 and 2 show respectively the IRAS 100 μm emission and the visual scattering at 0.5 μm of the cirrus cloud G230-28N.

The 60 μm emission of cirrus is also found to be correlated with the 100 μm emission (Harwit *et al.*[8], Laureijs *et al.*[9]). If the 60 μm emission were due to the same population of dust particles that radiate at 100 μm, we expect a brightness ratio $I(60)/I(100) = 0.11$[4]. However the observed 60/100 ratio of these clouds varies from region to region and is on average higher by a factor of two[8,9], requiring grain temperatures of the order of 24 K.

Figure 3 shows the temperature map of the cloud G230-28N derived from the 60 and 100 μm emission, under the assumption that the emission is caused by one

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population of dust particles radiating as a blackbody with an emissivity proportional to λ^{-1}. Note the nearly constant temperature in the outer parts of the cloud corresponding to 60/100=0.2 and the steep rise towards the centre of the cloud (60/100=0.24).

Recently the dust temperatures of cirrus clouds have been estimated through mm measurements by Andreani *et al.*[10], who find dust temperatures well below 20 K.

We therefore conclude that the IRAS 60/100 μm brightness ratio cannot be used to derive the cirrus dust temperature.

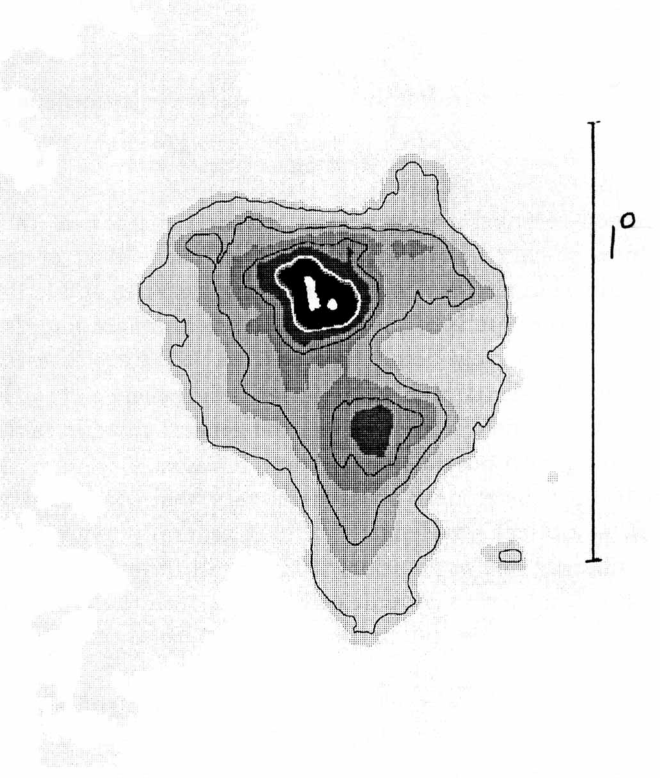

Fig. 1. IRAS 100 μm co-add map of the cirrus cloud G230-28N. The angular resolution is : $3.8' \times 6.4'$. Grey scales range from 0-5 MJy ster^{-1}, with darker grey scales corresponding to higher brightnesses. Contours are at 1...(1)...5 MJy ster^{-1}.

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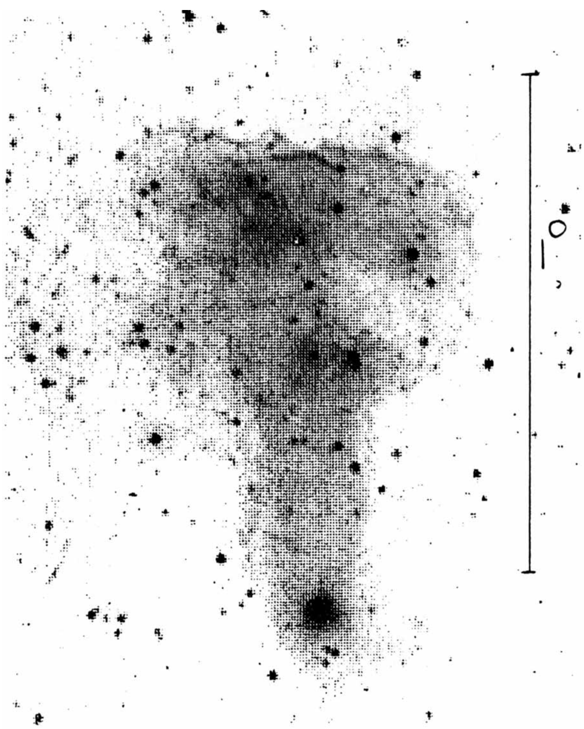

Fig. 2. Digitized (SERC IIIaJ) 0.5 μm surface brightness map of G230-28N, all but the brightest ($m_B < 10$ mag) stars have been removed. Darker grey scales correspond to higher brightnesses. Angular resolution : $22'' \times 22''$.

2. THE IRAS 60 μm EMISSION

What emission component can we expect to be present in the 60 μm band apart from dust continuum emission?

A population of very small grains (Draine and Anderson[11]) or large aromatic molecules (Puget *et al.*[12]) has been postulated to explain the IRAS infrared emission at 12 and 25 μm. This population of dust particles could also have an emission contribution to the 60 μm band. However the 12 and 25 μm emission have a different spatial distibution than the 60 μm emission[9,13].

Laureijs *et al.*[9] postulate a population of small iron grains with such a size distribution that the peak of the emission spectrum has a maximum in the IRAS 60 μm band. These grains would also contribute to the IRAS 25 and 100 μm bands.

A more plausible explanation is to assume a contribution of the neutral oxygen fine structure line, O°(63 μm), to the IRAS 60 μm band. This idea was first expressed by Harwit *et al.*[8], who suggested that the IRAS FIR radiation could

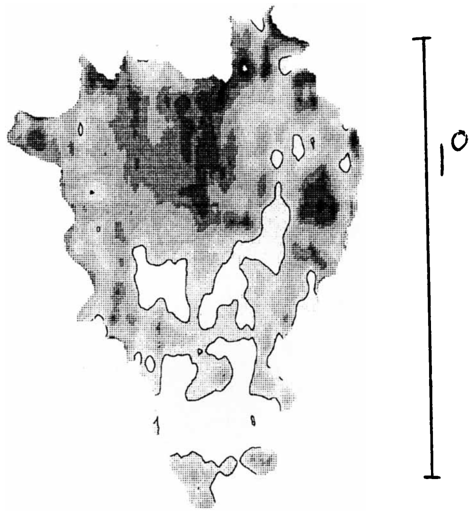

Fig. 3. Dust temperature map of G230-28N, assuming both 60 and 100 μm are caused by continuum emission of the same dust, modelled with a modified Planck function. Grey scales range from 22-28 K, darker grey scales correspond to higher temperatures. The contour is at 25 K.

be largely fine structure radiation of O^{o}(63 μm) and O^{2+}(88 μm). This explanation did not stick in the literature, probably because of the good correlation that was generally found of the 100 μm radiation with visual scattering and hydrogen column density, ruling out a contribution of O^{2+} emission.

Stark[14] has argued in a plausible way that a contribution of the neutal oxygen line to the dust continuum emission at 60 μm can account for the observed 60/100 brightness ratio and its variation in individual clouds. The observed 60 μm radiation can then be written as

$$I_{obs}(60\ \mu\mathrm{m}) = I_{O^{o}}(63\ \mu\mathrm{m}) + I_{dust}(60\ \mu\mathrm{m}) \qquad (1)$$

If we assume

$$I_{obs}(100\ \mu\mathrm{m}) = I_{dust}(100\ \mu\mathrm{m}) \quad \text{and} \quad \frac{I_{dust}(60\ \mu\mathrm{m})}{I_{dust}(100\ \mu\mathrm{m})} = 0.1$$

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we can write

$$I_{O^\circ}(63\ \mu\mathrm{m}) = I_{obs}(60\ \mu\mathrm{m}) - 0.1 I_{obs}(100\ \mu\mathrm{m}) \tag{2}$$

Figure 4 shows the thus obtained "oxygen-map" for G230-28N. The intensities range from 0.1 MJy ster^{-1} at the outerparts of the cloud to 0.7 MJy ster^{-1} at the cloud centre.

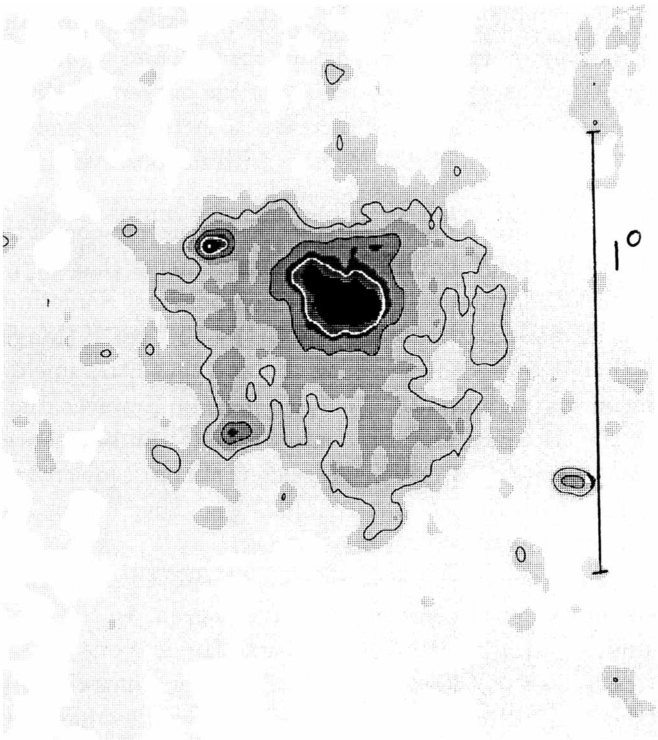

Fig. 4. "Oxygen-map"of G230-28N, derived from the IRAS 60 and 100 μm maps. Grey scales range from 0...0.7 MJy ster^{-1}. Contours are at 0.2, 0.4 and 0.6 MJy ster^{-1}.

3. DISCUSSION

We will discuss here the intensity of the oxygen line.

The intensity of an optically thin oxygen line can be written as :

$$I = \frac{1}{4\pi} n_H n_O \{L_H(O,T) + x_e L_e(O,T)\} d \tag{3}$$

where L_H and L_e are the cooling efficiencies for collisions between oxygen atoms with respectively hydrogen and electrons; n_H and n_O are the volume densities of hydrogen and O° respectively; x_e is the fractional ionization and d is the thickness of the cloud.

Stark[14] showed that a brightness of 0.1 MJy ster^{-1}($\equiv$2.6 10^{-6} erg cm^{-2} s^{-1} ster^{-1}) is obtained for $T = 100$ K n_H=270 cm^{-3} , $n_O = [O]/[H]n_H = 8.3\ 10^{-4} n_H$ (van Dishoeck and Black[15]) and $d = 1$ pc.

An increase of the oxygen line intensity towards the cloud centre (Fig. 4) cannot be explained from homogeneous cloud models[15,16]. However, if the cloud has a clumpy/filamentary structure, see Fig. 2, the radiation field (and thus the gas temperature) may be more or less constant through the whole cloud. As a result the line intensity goes as $n_H^2 d$. The increase of the oxygen line by a factor of 7 can then be explained as follows : $n_H d$ increases a factor of 3 and likewise does the density. The increase of $n_H d$ is in agreement with the observed increase of A_V from the edge (0.4) to the centre (1.1) of the cloud[13].

Additional evidence for a clumpy/filamentary structure comes from radio observations. Deul and Burton[20] find from H° measurements that cirrus clouds consist of superpositions of kinematically distinct components. Sometimes cirrus clouds contain significant molecular material : N(CO)$\sim 10^{16}$ cm^{-2} (Magnani *et al.*[21]). It is remarkable that clouds with such a low A_V and thus little shielding against photodissociation, show a significant CO column density. However, the CO can survive if small dense clumps exist. Falgarone and Pérault[22] find evidence for clumpiness from CO measurements on a very small scale (0.02 pc) : discrete clumps of ^{13}CO coherently moving with the low density ^{12}CO gas. They adress these density contrasts to turbulent motions within the clouds.

The oxygen line could also be collisional excited through shocks. Shocks are possible if the shock speed exceeds the Alfvén speed, which is of the order of a few km s^{-1} under typical interstellar conditions. Indications for shocks come from digitized optical plates (e.g Fig. 2), which show sometimes sharp transitions from the cloud to the background sky at one side of the cloud, whereas the other side of the cloud shows a very smooth transition. This so called head-tail like structure is observed in a number of cirrus clouds (Odenwald and Rickard[17]).

However, shock layers are expected to be very narrow (of the order 0.03 pc[18,19]) and an increase of the oxygen line from the edge of the cloud towards its centre over a distance of 0.4 pc (see Fig. 4 and assuming a distance from the cloud to the Sun of 100 pc) is therefore hard to explain, unless the shock is coming in from behind the cloud.

4. CONCLUSIONS

We have found several indications that the oxygen line might contribute significantly to the IRAS 60 μm band. The brightnesses we find correspond to a line intensity of the order of $10^{-6} - 10^{-5}$ erg cm^{-2} s^{-1} ster^{-1}, from the cloud edge to its centre respectively. A direct measurement of the O°(63 μm) line is therefore badly needed. In addition, measurements of both the C$^+$(158 μm) and the

$O^o(63\ \mu m)$ FIR lines in combination with radio H^o and CO line studies would give important insights in the gas temperature and the energy budget of these diffuse clouds.

Using the values of n_H and T from Sect. 3 and $n_{C+} = 0.4[C]/[H]n_H = 1.9\ 10^{-4}n_H$ (van Dishoeck and Black[15]), we predict (analogous to Eq.(3)) the C^+ line intensity to be a factor 10 stronger than the O^o line.

Today, only the NASA Kuiper Airborne Observatory is well suited to perform such a FIR study. The ESA Infrared Space Observatory, to be launched in 1993, will be capable to study many of the important FIR lines in a large number of cirrus clouds.

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