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COBE[1]/DIRBE OBSERVATIONS OF THE ORION CONSTELLATION FROM THE NEAR- TO FAR-INFRARED

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RESUMEN

La inyección de energía de las estrellas masivas es dominante en las regiones de formación estelar. Por lo tanto, es importante saber la fracción de energía que es absorbida por el polvo y cuánto escapa de la región. Con observaciones IR tomadas con el instrumento DIRBE, a bordo del satélite *COBE*, se obtiene la energía luminosa en un área de ~ 240 pc × 80 pc en Orión. Las observaciones en el infrarrojo medio y lejano son ideales para determinar la cantidad de energía absorbida por el polvo.

ABSTRACT

The energetics of star-forming regions is dominated by the energy output of the most massive stars. Consequently, it is crucial for the understanding of star-forming regions to know how much of this energy from massive stars is absorbed by the surrounding interstellar dust and how much escapes. Using infrared observations from the DIRBE instrument aboard the *COBE* spacecraft, a budget for the luminous energy for the ~ 240 pc × 80 pc area of the Orion star-forming region is presented. Mid-infrared and far-infrared observations are ideal for estimating the proportion of absorbed luminous stellar energy because it is this energy —absorbed by dust grains at shorter wavelengths and reprocessed— that is observed in the mid-infrared and far-infrared.

Key words: **DUST, EXTINCTION — INFRARED: GALAXIES — STARS: FORMATION**

1. INTRODUCTION

The energetics of star-forming regions with OB stars is dominated by the luminosity of these OB stars. For example, the Orion OBI and λ Orionis OB associations together have more than 500 stars (Warren & Hesser 1977; Murdin & Penston 1977), but 80% of the total stellar luminosity comes from just 8 stars with spectral classes between O7 and B0. Hence, it is important to know how much of this energy is absorbed by the local dust, and reprocessed to longer wavelengths, and how much escapes. This energy budget is important for estimating the following:

- How much stellar luminous energy is available to potentially influence the star-forming region.
- How much ultraviolet light "leaks" out of the star-forming region and hence contributes to the galactic scale or general interstellar radiation field (GISRF).
- How much of the energy leaked from other star-forming regions —this leaked energy comprising the GISRF— is available to influence the star-forming region under study.

The energy budget thus consists of the energy available for the influence of size-scale on size-scale: the local-scale on the local-scale, the local-scale on the global-scale, and the global-scale on the local-scale.

The question of how much energy from OB associations escapes to large distances was investigated by Leisawitz & Hauser (1988), who studied a small sample of OB associations and their associated H II regions and molecular clouds. They concluded that roughly 60% of an O star's total radiated energy over its lifetime escapes to large distances and, consequently, massive stars can contribute substantially to dust heating throughout the

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Galaxy. Another more direct test for the amount of locally-absorbed starlight is to compare the total luminosity of the stars with the mid-infrared (MIR) and far-infrared (FIR) luminosities of the associated interstellar matter. This is a direct test because the MIR and FIR emission is the actual locally-absorbed stellar light after reprocessing to longer wavelengths by dust grains. This direct test is covered in more detail by Wall et al. (1996) and is the subject of this article.

Orion is the nearest (450 parsecs) site of OB star formation and has the nearest Giant Molecular Clouds (see the review by Genzel & Stutzki 1989 and references therein). The *Diffuse InfraRed Background Experiment (DIRBE)* aboard NASA's *COsmic Background Explorer (COBE)* satellite, as part of its all-sky survey, mapped the entire Orion Constellation in ten infrared bands: λ = 1.25, 2.2, 3.5, 4.9, 12, 25, 60, 100, 140, and 240 μm (Hauser et al. 1991). Using these data, the proportion of dust heating attributable to the general interstellar radiation field (GISRF) as opposed to the stars of Orion is estimated.

The results of this article concentrate on three large circular fields with diameters = 10°-12°, which were chosen to enclose prominent molecular clouds or features (i.e., Orion A and B molecular clouds and the λ Orionis Ring). The fields represent a swath roughly 30° long and 10° wide (~240 pc × 80 pc) or a solid angle of 0.083 sr (16900 pc^2). All maps were cleaned of zodiacal emission or zodiacal scattered light. To remove foreground and background emission associated with the Galactic plane, a cosecant-law background of the form $a_c csc(|b|)$ was subtracted from the maps, where b is Galactic latitude and a_c is a scale factor. For more details, the reader is encouraged to consult Wall et al. (1996).

2. ENERGY BUDGET: ORION STARS VERSUS GISRF

To estimate the total luminosity of interstellar dust thermal emission, the 12 to 240 μm maps were added together, appropriately weighted, to generate a surface luminosity map of the dust. The total dust luminosity, L(12-240 μm), from the three Orion fields is about $10^6\,L_\odot$. When compared with the total stellar luminosity of $2.5 \times 10^6\,L_\odot$, we can see that at least 60% of the stellar energy is escaping the Orion region without being absorbed by dust. Given that a large fraction of the stellar luminosity can escape from a star-forming region, it follows that this escaped luminosity creates a galactic-scale or general interstellar radiation field (GISRF) that will contribute to the heating of other star-forming regions. Hence, the thermal dust luminosity budget of the Orion region will have a contribution from the GISRF as well as from the local Orion stars.

To estimate the local and non-local contributions to this energy budget, it is assumed that the GISRF has a constant energy density on scales of hundreds of parsecs (i.e., scales much larger than the Orion Fields) and that the Orion stars provide a localized enhancement to the interstellar radiation field. For the GISRF, the value for the local interstellar radiation field determined by Mathis et al. (1983) is adopted. Their estimated wavelength-integrated mean intensity is $U_G \equiv \int_{0.09\,\mu m}^{8\,\mu m} 4\pi J_\lambda\, d\lambda = 2.2 \times 10^{-2}\,erg \cdot s^{-1} \cdot cm^{-2}$, which corresponds to $50\,L_\odot \cdot pc^{-2}$. To make this estimate it was necessary to first derive a map of the radiation field in Orion.

2.1. Maps of the Radiation Field

Deriving a map of the radiation field strength in Orion requires detailed knowledge of the positions of the stars and dust in three dimensions, and detailed knowledge of their properties. Since precise depth perception is not possible, we are restricted to a simplified two-dimensional geometry. Using this simplified geometry and the positions and luminosities of the stars of Orion OB1 and λ Orionis OB associations (Warren & Hesser 1977; Murdin & Penston 1977) a map of the interstellar radiation field in Orion was derived with the assumptions that all the material is in a plane normal to the line-of-sight at a distance of 450 pc, that the stars are offset from this plane to prevent singularities in the radiation field derivation (see Wall et al. 1996 for details), and that stars not included in Warren & Hesser (1977) or Murdin & Penston (1977) make a negligible contribution to Orion's radiation field. Another implicit assumption in determining the radiation field is that there must be extinction between each star k and each position on the sky, as represented by a pixel (i,j). With extinction effects, the radiation field due to Orion's stars at pixel (i,j) is given by

$$U_\star(i,j) = \sum_k \frac{L_k \exp\left(-\tau_k(i,j)\right)}{4\pi\left(r_k^2(i,j) + d_k^2\right)}. \qquad (1)$$

L_k is the luminosity of star k, $r_k(i,j)$ is the projected distance from star k to pixel (i,j) in the "plane" of the cloud, d_k is the line-of-sight offset discussed above, and $\tau_k(i,j)$ is the optical depth on the line joining star k to pixel (i,j).

Due to a lack of detailed depth perception, there is no unique way to determine $\tau_k(i,j)$. It is necessary to assume some reasonable variation of the volume density along the path from star k to pixel (i,j). The volume density variation along a given path was assumed to be identical to that of the observed line-of-sight column density along this path. This treatment is unrealistic because it assumes a constant line-of-sight depth everywhere but is probably more realistic than assuming a constant density everywhere. The free parameter to be estimated in this treatment is a column density to volume density conversion factor, c_v. We created 3 radiation field maps, each with its own value of c_v: $5 \times 10^{-21} cm^{-1}$, $5 \times 10^{-20} cm^{-1}$, and $5 \times 10^{-19} cm^{-1}$.

To choose the correct radiation field map (i.e., choose c_v), we must find which map best reproduces the observed dust luminosity map, $\mathcal{L}_{dust}$ or $\mathcal{L}(12-240\,\mu m)$. Dust luminosity is re-emission of the absorbed radiation field. If a blob of dust and gas absorbing the radiation field has column density $N(H)_{dust}$, then the observed dust surface luminosity is given by

$$\mathcal{L}_{dust} = (U_\star + U_G)\left[1 - \exp\left(\frac{-N(H)_{dust}}{1.6 \times 10^{21}\,cm^{-2}}\,f\right)\right] \quad , \qquad (2)$$

with U_G as the contribution by the GISRF (using $U_G = 50\,L_\odot \cdot pc^{-2}$) and where f is a correction factor that converts the extinction in V-band to an absorption optical depth. The factor f corrects for porosity (i.e., clumping), for the possibility of the effective wavelength of absorption being outside of the V-band, and for scattering. The combination $c_v = 5 \times 10^{-21} cm^{-1}$ and $f = 0.3$ best reproduces the observed dust luminosity.

2.2. Proportion of Dust Luminosity from GISRF-Heated Dust

From modeling the dust luminosity map, we know that the absorption optical depth is approximated by $N(H)_{dust}\, f/1.6 \times 10^{21} cm^{-2}$ with $f = 0.3$. The surface luminosity due to dust heated by the GISRF is then given by equation (2) with $U_\star$ set to zero. This modified form of equation (2) and the observed dust luminosity gives us the fraction due to GISRF-heated dust: 24%.

The shapes of spectral distributions themselves can provide estimates of the fraction of dust luminosity due to dust heated mainly by the GISRF. We used the models of Désert et al. (1990) to investigate this in more detail, combining their dark cloud models (GISRF with extinction) and their O5-star dust-heated models so as to match the observed spectral distributions. The best fit of the models to the observations suggests that the GISRF-heated dust accounts for 36% of the dust luminosity from Orion, in reasonable agreement with the method described above.

This is the first global estimate of L_{GISRF}/L_{dust} for the Orion region with such a comprehensive data set.

3. CONCLUSIONS

It can be concluded that roughly 30%, or $3 \times 10^5\, L_\odot$, of the dust luminosity from Orion is due to dust mainly heated by the GISRF; the remaining $7 \times 10^5\, L_\odot$ of dust luminosity comes from the absorbed light of the Orion stars. Hence, roughly $1.8 \times 10^6\, L_\odot$ or 70% of the luminosity of the Orion stars escapes *unabsorbed*. Therefore, as concluded by Leisawitz & Hauser (1988), massive stars can contribute appreciably to the large-scale dust heating of the Galaxy, especially those stars in star-forming regions that are more than a few million years old (e.g., see Brown et al. 1994), and thus have naked O stars.

REFERENCES

Brown, A. G. A., de Geus, E. J., & de Zeeuw, P. T. 1994, A&A, 289, 101
Désert, F.-X., Boulanger, F., & Puget, J. L. 1990, A&A, 237, 215
Genzel, R., & Stutzki, J. 1989, ARA&A, 27, 41
Hauser, M. G. et al. 1991, AIP Conf. Proc., 222, After the First Three Minutes, ed. S. Holt, C. Bennett, & V. Trimble (New York: AIP), 161
Leisawitz, D. & Hauser, M. G. 1988, ApJ, 332, 954
Mathis, J. S., Mezger, P. G., & Panagia, N. 1983, A&A, 128, 212
Murdin, P. & Penston, M. V. 1977, MNRAS, 181, 657
Wall, W. F., et al. 1996, ApJ, 456, 566
Warren, W. H., & Hesser, J. E. 1977, ApJS, 34, 115