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GAMMA RAYS FROM GIANT MOLECULAR CLOUDS

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ABSTRACT

Giant Molecular Clouds (GMCs) are massive, bounded, cool, dense regions containing mostly H_2, but also HI, CO, and other molecules. These clouds occupy < 1% of the galactic volume, but are a substantial part of the interstellar mass. They are irradiated by the high energy cosmic rays which are possibly modulated by the matter and magnetic fields within the clouds. The product of cosmic-ray flux and matter density is traced by the emission of high energy gamma-rays. In this paper, we consider a spherical cloud model and predict the gamma ray flux from several GMCs within 1 kpc of the sun which should be detectable by the EGRET instrument on GRO.

I. INTRODUCTION

Interaction of cosmic rays with matter in molecular clouds, containing mostly H_2, but also HI, CO, and other molecules, produces high energy gamma rays. These gamma rays pass nearly unattenuated through the galaxy and thus, are a good tracer of the product of the cosmic ray flux and the matter density at distant places in our galaxy. The density of HI in these clouds can be observed directly. In cool, dense clouds, the H_2 density can be inferred from the intensity of the CO, $J = 1 \rightarrow 0$ transition. If the HI and CO radio observations accurately represent the matter distribution in molecular clouds then the local cosmic ray flux at these clouds can be determined from the gamma ray flux.

The gamma ray production rate as a function of the line of sight matter density, or source function, has been calculated for the Orion clouds by Bloemen, et al. (1984b). They used the CO data from Maddalena, et al. (1986), the HI data derived from Heiles and Habing (1974, $b < -10°$) and Weaver and Williams (1973, $b > -10°$) and the COS-B gamma ray data, Mayer-Hasselwander, et.al. (1982), with a maximum-likelihood technique to derive the parameters in the relationship

$$I_\gamma = A \cdot N(\mathrm{HI}) + B \cdot W_{\mathrm{CO}} + C$$

where A is the gamma ray production rate per H atom, B is the average $N(H_2)/W_{\mathrm{CO}}$ ratio multiplied by the gamma ray production rate per H_2 molecule and C is the isotropic galactic diffuse emission and instrumental background level. The CO and HI data were smoothed to match the 1.5° point spread function of COS-B. For $198° < l < 222°$ and $-25° < b < -5°$ their results are:

Energy Range	300 - 5000 [MeV]	100 - 5000 [MeV]
A [$\gamma\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\,\mathrm{atom}^{-1}$]	$(0.52 \pm 0.13)\,10^{-26}$	$(1.70 \pm 0.25)\,10^{-26}$
B [$\gamma\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{K}^{-1}\,(\mathrm{km/s})^{-1}$]	$(2.7 \pm 1.0)\,10^{-6}$	$(10.1 \pm 1.8)\,10^{-6}$
C [$\gamma\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$]	$(2.0 \pm 0.4)\,10^{-5}$	$(5.1 \pm 0.4)\,10^{-5}$
$N(H_2)/W_{\mathrm{CO}} = B/2A$ [$\mathrm{mol\,cm^{-2}\,K^{-1}\,km^{-1}\,s}$]	$(2.6 \pm 1.2)\,10^{20}$	$(3.0 \pm 0.7)\,10^{20}$

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The value of $A(300-5000\ \mathrm{MeV})$ found is consistent with the average emissivity value determined by Strong, et al. (1982) $(0.59\pm\sim 10\%)\cdot 10^{-26}\,\gamma\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{atom}^{-1}$ using medium latitude galaxy counts and by Bloemen, et al. (1984a) $(0.53\pm 0.14)\cdot 10^{-26}\,\gamma\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{atom}^{-1}$ from the radial distribution of the gamma ray emissivity in the outer galaxy.

The local cosmic ray source strength has most recently been derived by Strong, et al. (1988), by fitting the CO and HI survey data, inverse compton emission, isotropic background and point source contribution to the COS-B diffuse galactic gamma ray emission. They did the fit for six galactocentric rings, 2-4, 4-8, 8-10, 10-12, 12-15 and > 15 kpc ($R_\odot = 10$ kpc), and three energy ranges, 70-150, 150-300 and 300-5000 MeV. Their results, for 8< R < 12 kpc, are

$$q_0 = \begin{cases} 1.02\pm 0.10\times 10^{-26}\,\gamma\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\,\mathrm{atom}^{-1} & (70 < \mathrm{E} < 150\ \mathrm{MeV}) \\ 0.65\pm 0.06\times 10^{-26} & (150 < \mathrm{E} < 300\ \mathrm{MeV}) \\ 0.62\pm 0.06\times 10^{-26} & (300 < \mathrm{E} < 5000\ \mathrm{MeV}) \end{cases}$$

Most source strengths are quoted for the energy range E> 100 MeV. Assuming a power law spectra with index −2.1, the above results can be expressed in the form

$$q_0 = \begin{cases} 3.7\times 10^{-5}\,\gamma\,\mathrm{mg}^{-1}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1} & (20 < \mathrm{E} < 100\ \mathrm{MeV}) \\ 1.0\times 10^{-5} & (\mathrm{E} > 100\ \mathrm{MeV}) \end{cases}$$

We will use the this source function and a spherically symmetric GMC model with radially dependent density to predict the gamma ray emission of GMCs which will be observable by EGRET.

II. SPHERICAL CLOUD MODEL

Following Solomon et al. (1987), to model the gamma ray emission from GMC's, we consider the simplified case of a spherically symmetric cloud with radial density of the form

$$\rho(\mathrm{r})[\mathrm{g\,cm}^{-3}] = \rho_0\cdot(\mathrm{R}_0/\mathrm{r})^{\alpha}$$

where R_0 is the cloud radius. The line of sight column density is given by

$$\sigma(r)[\mathrm{g\,cm}^{-2}] = 2\int_0^{\sqrt{\mathrm{R}_0^2-r^2}} \rho(\mathrm{r}=\sqrt{r^2+x^2})\,dx$$

where r is the radial distance between the cloud center and the line of sight, or "impact parameter". Figure 1 shows the line of sight column density for $\alpha = 0$, 1 and 2 normalized for clouds with $\mathrm{M} = 10^6\,\mathrm{M}_\odot$ and $\mathrm{R} = 50\,\mathrm{pc}$ as a function of r. A similar model for cloud density was used by MacLaren, et al. (1988) who normalized the density at $\mathrm{r}/\mathrm{R}_0 = 0.55$.

Analysis of the CO data by MacLaren, et al. (1988), shown in figure 2 , suggests that α is close to 1, but it may be almost 2 for some clouds. This can also be seen by comparing the $\alpha = 1$ column density with the W_{CO} contours of the Orion A and B cloud peaks in figures 6 and 7 of Maddalena, et al. (1986). The peak at ($\alpha = 5^{\mathrm{h}}44^{\mathrm{m}}$, $\delta = 0°$), for example, has a fairly linear density fall-off with radial distance from the peak and a long tail. We include $\alpha = 0$ and 2 as limiting cases.

III. PREDICTED EMISSION OBSERVED BY EGRET

The diffuse galactic gamma ray spectrum above about 10 MeV is composed of an $\mathrm{E}^{-2.5}$ Brehmstrahlung component and the π^0 decay spectrum centered at about 70 MeV. We will consider here gamma rays with energies above about 100 MeV, where the π^0 spectrum begins to dominate. The effective area of EGRET in this energy region is about $1460\,\mathrm{cm}^2$.

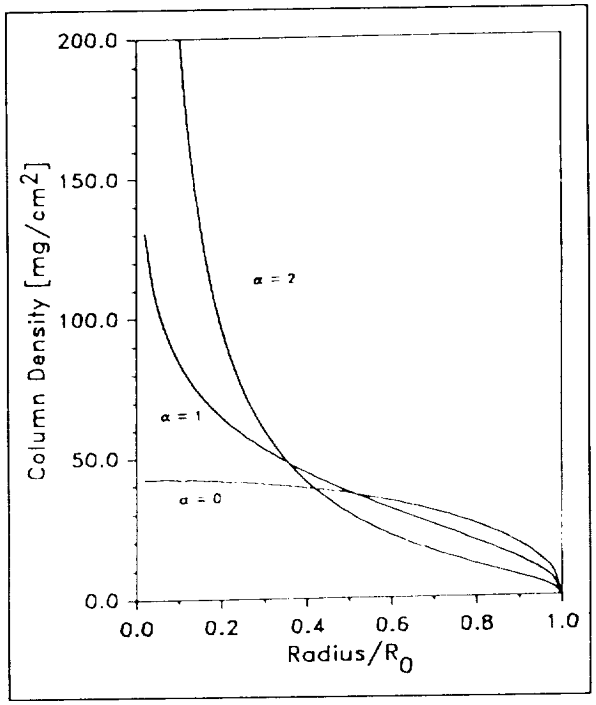

Figure 1. Column density as a function of impact parameter for a cloud with density given by $\rho = \rho_0 \cdot (R_0/r)^{\alpha}$, for $\alpha = 0$, 1 and 2, normalized to the same total mass, $M = 10^6\, M_{\odot}$, and radius, $R = 50\,pc$.

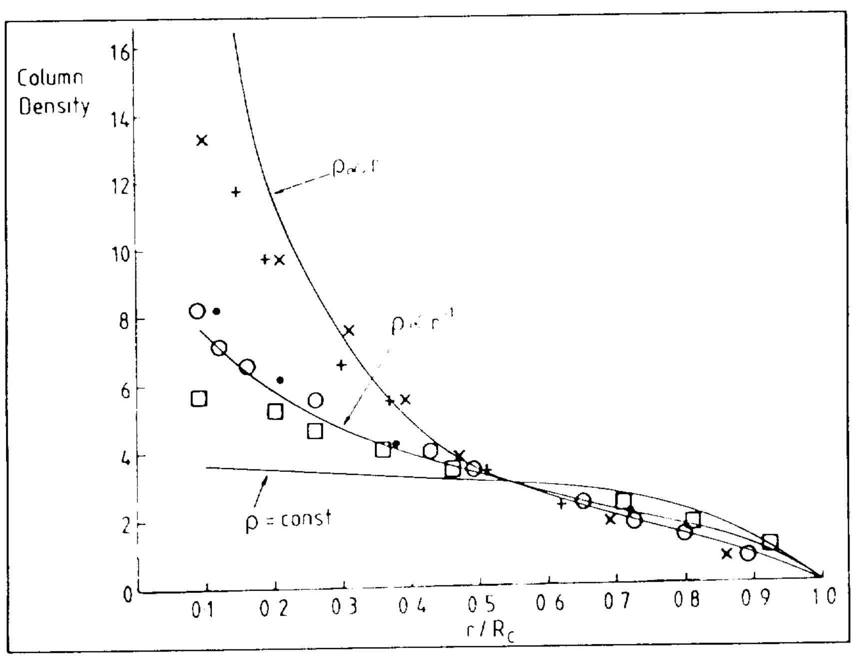

Figure 2. Column density of hydrogen (arbitrary units) derived from CO data vs. normalized cloud radius for several local molecular clouds. The solid curves are column densities for spherical clouds with density given by $\rho = \rho_0 \cdot (R_0/r)^{\alpha}$, for $\alpha = 0$, 1 and 2, normalized at $r/R_0 = 0.55$. Orion(A+B), (+); Taurus, (o); Perseus, (× and ▫). From MacLaren et al. (1988).

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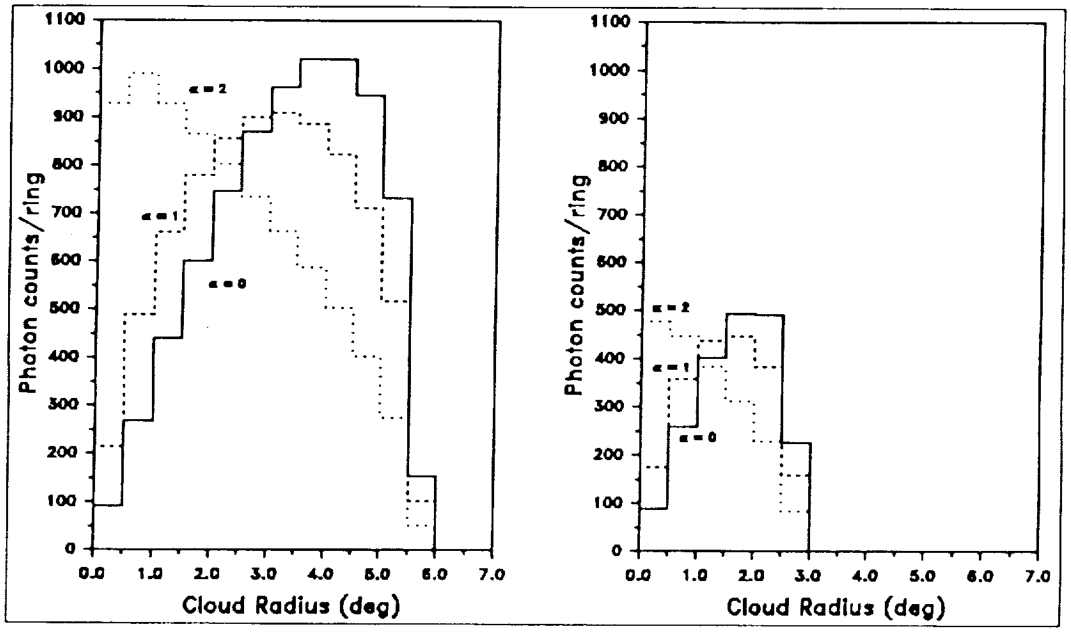

Figure 3. Number of gamma rays observed from a hypothetical GMC with cloud density given by $\rho = \rho_0 \cdot (R_0/r)^\alpha$, for $\alpha = 0$, 1, and 2, $M = 10^6 M_\odot$, $R_0 = 20\,pc$ at $D = 500\,pc$ (left) and 1000 pc (right). The total counts for $T_{obs} = 6 \times 10^5\,s$ are given per 0.5° ring.

To match the EGRET instrument angular resolution of about 0.5° for gamma ray energies above 100 MeV, it is appropriate to sum the total number of gamma-rays observed from a cloud into rings of width 0.5°. Thus, the total line of sight mass of a ring with inner radius r_1 and outer radius r_2 is given by

$$\Sigma(r_1, r_2)[g] = 2\pi \int_{r_1}^{r_2} r \cdot \sigma(r)\, dr$$

If all the sources of gamma ray production in the cloud can be expressed in terms of a single source function, such as that derived by Strong, et al. (1988), then the approximate gamma ray flux from the ring is

$$\text{Counts/ring}[\gamma\, sr^{-1}\, s^{-1}] = f \cdot q_0 \cdot \Sigma(r_1, r_2)$$

where $q_0\,[\gamma\, g^{-1}\, sr^{-1}\, s^{-1}]$ is the local cosmic ray source function and f is the relative cosmic ray intensity at the cloud. The calculation of the number of observed gamma ray from a GMC requires knowledge of the total mass of the cloud and the distance to the cloud in addition to the sensitivity or effective area of the detector.

$$\text{Counts}_{obs}\text{/ring} = A_{eff} \cdot T_{obs} \cdot 4\pi/4\pi D^2 \cdot \text{Counts/ring}$$

where $A_{eff}\,[cm^2]$ is the energy dependent effective area, $T_{obs}\,[s]$ is the observation time and $D\,[cm]$ is the distance to the cloud.

In figure 3 the number of counts, $E > 100$ MeV, per 0.5° ring are shown for a hypothetical $10^6 M_\odot$ cloud with 50 pc radius immersed in cosmic rays of the local density ($f = 1$) for an observation time of 6×10^5 s (effective time for a two week observation) at a distance of 500 and 1000 pc respectively. The diffuse galactic and extra-galactic gamma ray emission has not been included. Significant differences in the count profile can be seen for the different values of α. For $\alpha = 0$ the cloud appears very much as a ring with a sharp edge. For $\alpha = 1$ the ring structure is still visible, but the edge is softer. For $\alpha = 2$ the cloud appears as a bright spot with a soft edge.

We have calculated the number of gamma rays which EGRET can expect to observe in a typical two week observation for the clouds listed in table 1. These clouds, selected from the work by Dame et al. (1987), are more than 25 pc above or below the galactic plane, within 1 kpc of the sun and have masses greater than 1×10^4 $M_\odot$, see figure 4 .

TABLE 1

	l^o_{min}	l^o_{max}	b^o_{min}	b^o_{max}	D[pc]	M[10^5 $M_\odot$]
Cygnus OB7	87.0	99.0	-3.0	8.0	800	7.5
Cepheus	100.0	120.0	11.0	22.0	450	1.9
Taurus	163.0	178.0	-22.0	-9.5	140	0.3
Orion B	202.5	208.0	-21.0	-6.0	500	1.7
Orion A	208.5	218.0	-21.0	-14.5	500	1.6
Chamaeleon	295.0	305.0	-20.0	-12.0	215	0.1

From Dame et al. (1987)

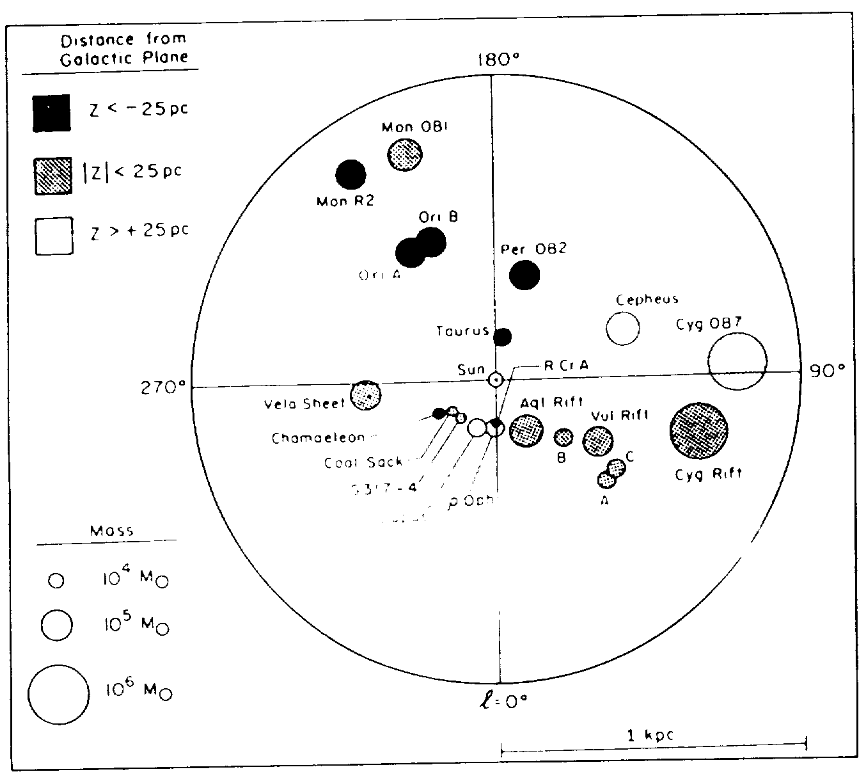

Figure 4. The distribution of GMCs with mass greater than 1×10^4 $M_\odot$ within 1 kpc of the sun. Adapted from Dame et al. (1987).

Combining the emission data of Strong et al. (1988) with the mass, radius and distance data in Table 1, we can calculate the high energy (E > 100 MeV) gamma ray emission from these clouds. Figure 5 , a, b and c, shows the estimated number of gamma rays (E > 100 MeV which will be observed from each of these clouds during a two week observation (6×10^5 s) summed into 0.5° circular bins. In each figure, the diagonal dotted line is the estimated number of counts from the diffuse emission for the same observation. The diffuse gamma ray emission (E > 100 MeV was estimated using the data given by Fichtel et al. (1978). The appropriate longitude data was averaged over the width of the cloud in latitude.

We now consider the statistical significance of these observations in two ways. The significance of the gamma ray observed in a ring over the background reaches a broad maximum at about 30% of the cloud radius and falls to zero at the cloud edge, as defined by the model. The significance of the total number of gamma rays observed from a cloud over the background reaches a maximum at about 82% of the cloud radius and then starts to fall as the background begins to dominate the signal. These values are model dependent, however, it is clear that knowledge of the cloud radii will be important in the analysis of a wide field of view gamma ray observation to determine the gamma rays which are produced in molecular clouds. Table 2 gives the modeled detection significance (in standard deviations) of the ring of maximum significance and of the total cloud for the six clouds listed in table 1.

TABLE 2

	Significance of Maximum Ring	Significance of Total Cloud
Cygnus OB7	2.2	5.5
Cepheus	14.0	39.6
Taurus	23.5	64.0
Orion B	21.4	47.1
Orion A	24.4	50.7
Chamaeleon	6.9	15.1

(in standard deviations)

IV. CONCLUSION

Clouds with masses greater than about 10^5 $M_\odot$ and closer than about 1 kpc should be detectible with the EGRET instrument in a two week observation. In addition, local and cloud-to-cloud variations in the product of the column density and the cosmic ray density should be resolvable for many of these clouds. We expect to also be able to detect some clouds to distances of a several kpc, and should be able to use these clouds as tracers of the cosmic ray density in more distant parts of the galaxy.

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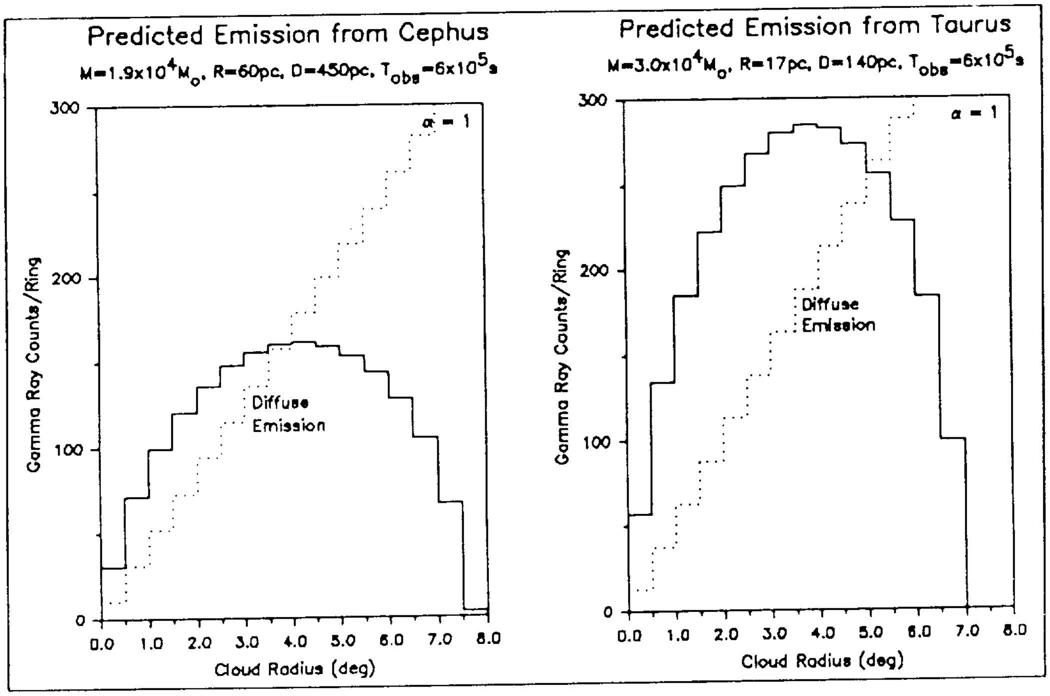

Figure 5.a Estimated gamma ray counts ($E > 100$MeV) from GMCs in Cephus (left) and Taurus (right) summed into 0.5° circles for a two week observation. The dotted line is the estimated diffuse emission for the same observations.

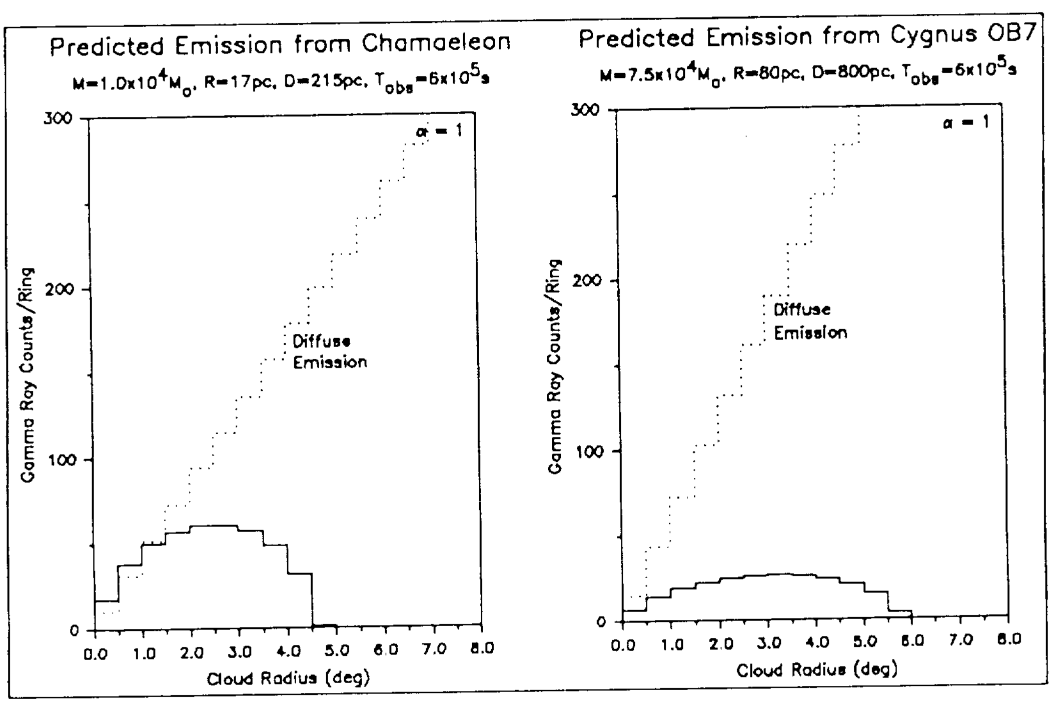

Figure 5.b Estimated gamma ray counts ($E > 100$MeV) from GMCs in Chamaeleon (left) and Cygnus (right) summed into 0.5° circles for a two week observation. The dotted line is the estimated diffuse emission for the same observations.

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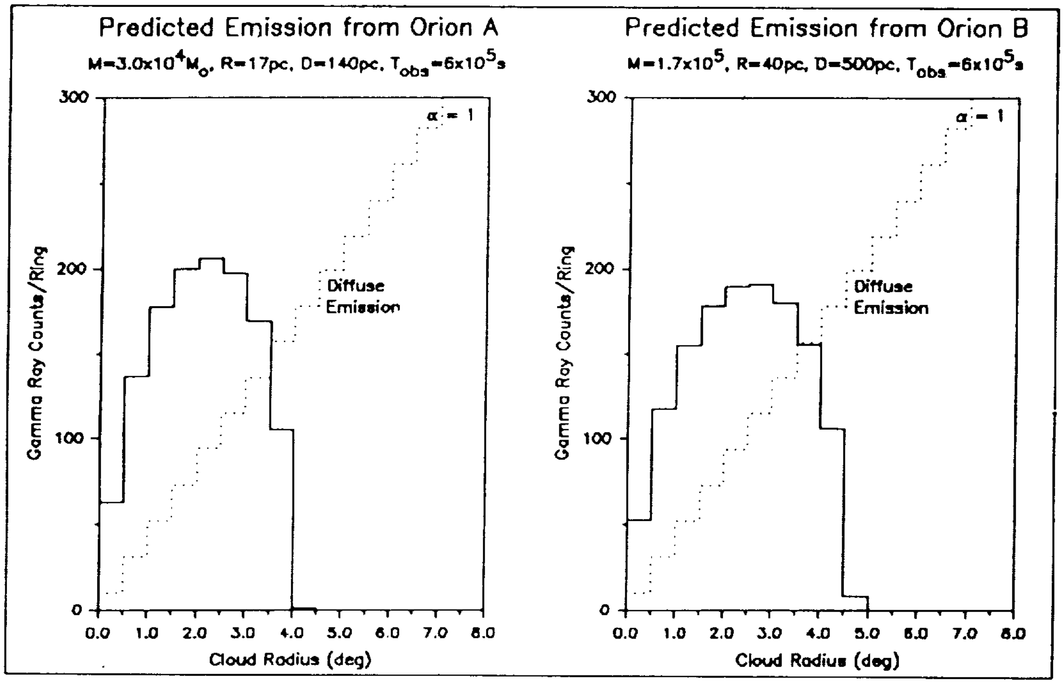

Figure 5.c Estimated gamma ray counts (E > 100MeV) from Orion_A (left) and Orion_B (right) summed into 0.5° circles for a two week observation. The dotted line is the estimated diffuse emission for the same observations.

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