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On the Nature of the COS-B Gamma-ray Source CG 353+16

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Summary. The recently proposed nearby ($d \sim 0.03$ pc) cloud of Vidal-Madjar et al. (1978) has an angular extent encompassing the ϱ Oph region and the COS-B CG 353 + 16 source. In an attempt to analyse a possible association between the γ-ray source and the cloud, usage is made of SAS-3 low energy X-ray data to put an upper limit on the columnar density, and thus such an association can easily be excluded. Furthermore, the possibility is analyzed that the COS-B source be associated with the ϱ Oph dark cloud complex, and that the responsible process be the interaction of cosmic rays (CR) with the cloud mass. It is seen that a "standard" Black and Fazio (1973) mechanism can hardly be at work so that the quantitative requirements are given for an improved γ-ray production rate, obtainable, for instance, within the model of Forman et al. (1979).

Key words: gamma-ray radiation – interstellar clouds

I. Introduction

Since the appearance of the dark ("black") cloud of Vidal-Madjar et al. (1978) in the Scorpius-Ophiuchus region of the sky, new data have become available from high-energy astrophysics, which are relevant to that general direction: the SAS-3 low-energy X-ray data of Apparao et al. (1979) and some new COS-B high-energy γ-ray data, namely the preliminary list of positions of new γ-ray sources, given by Mayer-Hasselwander et al. (1979). In particular, that list includes the source CG 353 + 16 which is in the direction of Ophiuchus and, in fact, the Caravane Collaboration reports it to be " in (the direction of the) Ophiuchus dark cloud complex". The purpose of the present work is to speculate on the nature of such a γ-ray source, which is conveniently placed at a galactic latitude (16°) where most of the confusion typical of the γ-ray disc is greatly reduced. It is interesting to note that even in the first generation balloon experiments of Dahlbacka et al. (1973) and Frye et al. (1972) the existence of a source was independently claimed in approximately the direction of ϱ Oph, but with alleged fluxes more than one order of magnitude on the high side. The results of the SAS-2 satellite (Fichtel et al., 1975; Hartman et al., 1979) were the first to recognize the general enhancement seen in the Ophiuchus-Lupus region to that in the Orion-Taurus. The short exposure time in the particular direction of ϱ Oph, however, only produced an upper limit, consistent with the flux value used here.

Obviously, the Vidal-Madjar et al. cloud, or part of it, presents itself as a good candidate, a priori, as it provides a rather substantial amount of matter in an extremely local position, 10^{-2} to 10^{-1} pc from the Sun. The local cosmic rays then could interact with the gas to produce high-energy γ-rays. However, when such a mechanism is considered in detail (see Sect. III) together with the constraints introduced by the X-ray data (Sect. II) it is apparent that a large contradiction is reached and that the γ-ray source has little chance of being in the foreground of the ϱ Oph complex (which is located at about 160 pc from the Sun). It is then more important to investigate the consequences of postulating that such a source is indeed associated with the ϱ Oph cloud complex, of which the relevant astronomical properties are reviewed. It will be readily seen (Sect. IV) that some special mechanism must be at work in order to account quantitatively for the γ-ray source and reference is made to one possibility. Finally, the consequences are explored of generalizing the results obtained for the particular case of ϱ Oph to most of the galactic cloud complexes making use of the total galactic γ-ray luminosity as a boundary condition.

II. The X-ray Data Constraint

The X-ray data of Apparao et al. (1979) cover the region of the sky $-28° < \delta < -21°$ and $242° < \alpha < 249°$, with the fluxes in the L-band (0.1–0.4 keV) ranging between ~ 13 and 40 photons $\mathrm{cm^{-2}\,s^{-1}}$ ster. Similar fluxes are reported in the M-band (0.4–0.8 keV), thus indicating a very hard spectrum, with a power law index of 0.4. Such a spectrum is consistent with that measured by Hayakawa et al. (1977, 1978) for the adjacent Loop I region (Hayakawa et al., 1979), and also the flux values smoothly join those in adjacent regions (see e.g. Tanaka and Bleeker, 1977 and references therein). From the lack of absorption at the ϱ Oph position, Apparao et al. conclude that most of the emission is in the foreground of the cloud complex (i.e. at distances less than 160 pc away). On the other hand, the proposed dark cloud of Vidal-Madjar et al. (1978) is also not seen in absorption when the Apparao et al. (1979) measurements are considered together with the large scale ones to which they smoothly join. It is concluded that the SAS-3 L-band measurements an upper limit of $\sim 10^{20}$ atoms $\mathrm{cm^{-2}}$ for the "truncated" columnar density in the general ϱ Oph direction. The addition of a clumping factor, $C\langle\varrho^2\rangle/\langle\varrho\rangle^2$ to the Brown and Gould (1970) absorption cross section cannot increase the per-

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mitted amount of matter by more than a factor of ~ 2; we shall then assume the columnar density in the foreground of ϱ Oph to be $\varrho L < 2\,10^{20}$ atoms cm^{-2}.

III. The γ-ray Data Constraint

It is interesting to speculate whether the COS-B γ-ray source CG 353+16 may be in the foreground of ϱ Oph, e.g. be associated with the Vidal-Madjar et al. cloud. The γ-ray emission in this case could be due to a "standard" Black and Fazio (1973) mechanism, i.e. interaction of the cosmic rays with the cloud material (see also Lebrun and Paul, 1978 and references therein). Assuming the CR to have the same spectrum as at the Sun, the most favourable case is the one where all the permitted matter along the truncated columnar density is concentrated in one cloud of density ϱ and diameter L, with the restriction obtained from the X-ray data

$\varrho L < 2\,10^{20}$ atoms cm^{-2}.

The angular extent of the γ-ray source (L/D, when D is its distance) has an upper limit, α, since it is "unresolved" in the γ-ray measurement. The exact value of α is one of the intrinsic uncertainties of γ-ray astronomy, and it is, more over, energy-dependent. We shall assume $\alpha = 1/20$ radian (above 100 MeV), consistent with the characteristics of the COS-B mission (Scarsi et al., 1977). Work for determining the source spectral shape as well as its integral flux (>100 MeV) is in progress, and for the present purposes we shall use a flux $\Phi_\gamma = 1.1\,10^{-6}$ photons (>100 MeV) cm^{-2} s^{-1}, (Wills et al., 1979), to which an uncertainty of a factor of 30% should be attached. The elementary γ-ray production rate via the CR-matter interactions has been the subject of ample work in the recent years (e.g. Stecker, 1977; Bignami et al., 1975; Cesarsky et al., 1978; Fichtel et al., 1978 and references therein, Webber et al., 1979). A value of $q_\gamma \simeq 2.5\,10^{-25}$ photons (>100 MeV) s^{-1} (H atom)$^{-1}$ will be adopted here, which implies the same CR spectrum as that measured in the vicinity of the Sun. For the γ-ray source to be in one cloud in the foreground of ϱ Oph one must then satisfy the following relations:

from γ-rays

$$L/D < \alpha \tag{1}$$

$$\Phi_\gamma = \frac{q_\gamma}{D^2}\frac{1}{3}\left(\frac{L}{2}\right)^3 \varrho \tag{2}$$

from X-rays

$$\varrho L < 2\,10^{20}. \tag{3}$$

From (2) and the inequality (1)

$$\varrho L \gtrsim 1.05\,10^{20}\frac{1}{\alpha^2}. \tag{4}$$

When we compare (4) with (3) using typical values for $\alpha \leqq \frac{1}{20}$ we see that there is an inconsistency which is far too large to be accounted for by inaccuracies in the values used for the parameters.

IV. Discussion

The above "reductio ad absurdum" implies that the COS-B γ-ray source CG 353+16 is indeed at a distance equal to or greater than that of the cloud complex ϱ Oph, and thus cannot be associated with the local cloud of Vidal-Madjar et al. (1978), notwithstanding the loose positional coincidence, unless an unrealistically high q_γ is assumed in the nearby cloud.

It is then tempting to associate the γ-ray source with the ϱ Oph dark cloud even on the basis of the sole positional overlap, because its galactic latitude value ($b \sim 16°$) makes for a short path length in the galactic disc ($\lesssim 500$ pc remain beyond ϱ Oph, with decreasing density) where to look for alternatives, and no special extragalactic object is apparent in that direction.

As to the mechanism of emission, the obvious candidate to consider is the interaction of cosmic rays with the gas of the cloud, first sketched by Blanck and Fazio (1973), who only considered the proton-proton interaction case. The problem of the penetration of cosmic rays in the cloud has been discussed in detail by Strong and Skilling (1976), and by Cesarsky and Völk (1978) who have shown that the majority of the high-energy particles do indeed penetrate the cloud, but that on the other side, no significant CR enhancement can be achieved in an equilibrium situation. Marscher and Brown (1978) have shown that moderate (~ 50%) increase in the secondary electron flux can take place. The most sensible step to take is to assume that the q_γ discussed above holds true at ϱ Oph as well.

As for the mass of the cloud complex ϱ Oph itself, several independent astronomical estimates are now available, based on optical absorption, radio measurements and infrared measurements. For a complete discussion of the subject we refer to the recent work of Elias (1979). The distance to the cloud is estimated at ~ 160 pc ± 10 in Encrenaz et al. (1975) and Whittet (1974). The mass estimate is in the region of a few $10^3\,M_\odot$ (e.g. Encrenaz et al., 1975) for the clouds within an angular extent of $\sim 1.5°$ which corresponds to a linear dimension of ~ 5 pc. The highest astronomically estimated mass found in the literature is that of Vrba (1977) with $\sim 6\,10^3\,M_\odot$ and we shall adopt this value here, well aware (Rossano, 1978 and private communication) that this is already on the high side. The mass estimate of Black and Fazio (1973) has to be neglected as unreasonable nowadays, since it was based on early balloon γ-ray data and moreover, their production rate neglected the electron contribution. It is then straightforward to see that with the q_γ, mass and distance estimates quoted above the γ-ray flux >100 MeV of the cloud should be at most $6.4\,10^{-7}$ photons cm^{-2} s^{-1} or less, considering the overestimate of the mass. Especially in a confused region of the sky, this value seems too low for being associated with the source CG 353+16. While maintaining the cloud complex as the astronomical source, and the CR-matter interaction as the responsible physical process, one can speculate on how to increase the γ-ray yield of the source. One natural possibility is that suggested by Forman et al. (1979) based on a shock-acceleration of CR close to the cloud.

It is interesting to see what implications arise if the high γ-ray luminosity of ϱ Oph is applied generally on a galactic scale. This is just speculation, of course, since use of a constant q_γ throughout the Galaxy implies a constancy of the CR flux which may not be the case, as suggested by a great number of authors. If one then takes $q_\gamma = 5\,10^{-25}$ photons (>100 MeV) s^{-1} (H atom)$^{-1}$, or the emissivity required to account for the flux of the COS-B source, and makes use of the boundary condition of the total galactic γ-ray luminosity (see e.g. Strong, 1975; Strong and Worrall, 1976; Bignami et al., 1975; Caraveo and Paul, 1979) observed to be $\sim 1\,10^{42}$ photons (>100 MeV) s^{-1}, then the total amount of gas necessary and sufficient to account for the γ-ray luminosity is $\sim 2\,10^{66}$ protons (or, rather, "equivalent H atoms"), or $\sim 1.6\,10^9\,M_\odot$. This number has to be compared to astronomical estimates of the total mass in gas or clouds in the Galaxy. For instance, Stark and Blitz (1978) point out that just the giant cloud complexes could account for as much as $\sim 2\,10^9\,M_\odot$. To this number one should add the integrated mass of smaller and much more numerous clouds, and the intercloud medium, a lower limit to the total mass of which can be roughly inferred from radio measurements (21 cm, CO lines etc.) to be $\gtrsim 5\%$ of the total mass of the galaxy, or $\sim 1\,10^{10}\,M_\odot$. If, then, CG 353+16 is associated with the ϱ Oph cloud complex, a relatively small fraction, $\sim 10\%$ or so, of all the gas in the Galaxy need behave like ϱ Oph in γ-rays to account for the total observed galactic γ-ray luminosity. This too can be taken as an indication of the special nature of the ϱ Oph cloud as a γ-ray source, and hence of the need of a higher CR density at it. Of course, other mechanisms and sources not associated with clouds are at work to produce γ-rays in the galaxy (as e.g. pulsars) and their contribution can be significant (see e.g. Bignami et al., 1978; Protheroe et al., 1979; Rothenflug and Caraveo, 1979). However, molecular clouds with increased γ-ray yields should be considered as an important contributing species.

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