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3C273 Revisited: Confirmation by COS-B of High Energy Gamma-ray Emission

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Summary. The results of a second observation in the Virgo region by the ESA COS-B satellite are presented. The presence of a high-energy (50–800 MeV) γ-radiation source is confirmed, and its position is consistent with 3C273. The error box at the 90% confidence level containing the quasar is ~ 2.5 square degrees, and the probability of a chance coincidence of the γ-ray source with 3C273 is approximately 10^{-3}. No variation of the γ-ray fluxes between the two observations in July 76 and June 78 is observed within the $\sim 50\%$ uncertainty. Spectral γ-ray data for the total 3C273 data set are presented and compared with low and high-energy X-ray contemporary measurements. Recent Einstein Observatory X-ray data on the short term variability of the central part of the QSO are used to show that, within reasonable assumptions, the photon-photon interaction excludes the γ-ray source from coinciding with the variable X-ray source, thus ruling out comptonisation models for the production of energetic photons.

Key words: COS-B – 3C273 – γ-ray source

1. Introduction

The discovery of the high-energy γ-ray source CG291+65 in the data of the COS-B mission has prompted Swanenburg et al. (1978) (hereinafter Paper 1) to propose its identification with the quasar 3C273 on the basis of the positional coincidence. Because of the size of the error-box, Paper 1 evaluated as $\lesssim 1\%$ the probability of a chance coincidence of the γ-ray source with the specific object 3C273. Here, the results of a second COS-B observation of the same region of the sky are reported: the source is seen again and the increased statistics yield a much better positional determination.

This confirms the identification of 3C273 as the first extra-galactic source of γ-rays in this energy range. The use of the combined data set permits the derivation of a spectrum in the 50 to 800 MeV interval, and of an upper limit on long term variability.

A comparison of the COS-B data with satellite X-ray measurements is especially stimulated by the recent Einstein Observatory data on the time variation of the X-ray emission.

2. Observation and Results

The second observation by the ESA COS-B γ-ray satellite in the direction of the Virgo region of the sky was performed between 9th June and 17th July, 1978 with the axis of the satellite pointing towards $\alpha_{(1950)} = 12^h26^m$ and $\delta_{(1950)} = +2°24'$, and an effective field of view of about 20° radius. A total of ~ 3000 γ-rays (> 50 MeV) were accepted for this period, including photons from the celestial and instrumental backgrounds. The individual arrival directions and energies were derived with the procedure outlined by Scarsi et al. (1977). The arrival directions were analysed with a "cross correlation" method to search for localised sources. Briefly, the cross correlation method, used also for the analysis of the data of Paper 1, consists in correlating the distribution of photon arrival directions, organized in matrices, with the standard distribution, or profile, (point spread function) expected as the response of the instrument to a point-like source. This response is known both from pre-flight calibration and from the PSR 0833-45 data (Scarsi et al., 1977). The size of the matrix in the sky over which the correlation is computed, as well as the shape of the profile to be correlated can be selected according to the energy range. The search for sources is carried out for energies above 100 MeV with a correlation matrix of 15° × 15°, and with a point spread function which could be approximated by $f(\theta) = \exp(-\theta/1.^\circ 25)$.

The results are judged in terms of confidence level (in standard deviations from an assumed flat background) of the excess, and of the actual number of correlated photons. The probability calculation has been verified by Monte Carlo simulations.

Table 1 gives, for each observation period as well as for the combined data, the points of maximum significance, the confidence levels at those points and the correlated counts associated with those levels. As could be expected, the position given by the combined data is intermediate between the individual positions, all being consistent with the position of 3C273, and the combined correlated counts are less than the sum of the individual maxima. The confidence levels and correlated counts at the position of 3C273 are also given in Table 1, showing the increased significance obtained from the combined data.

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Table 1

Observation no. and dates	Point of max significance(POMS) $\alpha^{(\circ)}_{1950}$	$\delta^{(\circ)}_{1950}$	Confidence level at POMS (σ)	Correlated counts at POMS	Confidence level at 3C273 (σ)	Correlated counts at 3C273
10 24 May – 24 June, 1976	186.75	3.75	6.7	47 ± 13	5.4	37 ± 10
32 9 June – 17 July, 1978	184.75	2.25	5.0	34 ± 11	3.6	25 ± 9
10+32	185.75	2.25	6.8	66 ± 15	6.3	62 ± 14

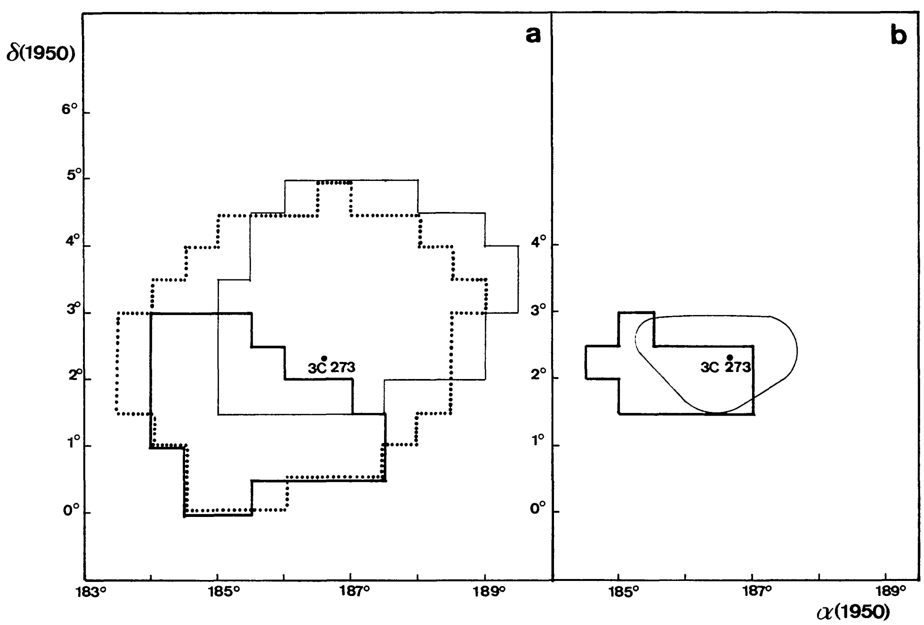

Fig. 1. a Area of the γ-ray sky around 3C273, showing the 4σ confidence level contours for observation 10 (thin line), 32 (thick line) and for the sum of both (dotted line), as derived from the cross-correlation method. **b** Comparison of the results derived with the cross-correlation and the likelihood methods applied to total data set (Periods 10 and 32 together). Thick line: 6σ contour derived with the cross-correlation method. Thin line: 90% confidence level contour with the likelihood method. The position of 3C273 is also shown

Figure 1a shows the 4σ confidence level contours for observations 10 and 32, as well as for the combined data set. In Fig. 1b it is seen that the position of 3C273 ($\alpha_{(1950)} = 186\overset{\circ}{.}63$, $\delta_{(1950)} = 2\overset{\circ}{.}325$) is within the 6σ contour.

The "likelihood" method of analysis has also been applied to the summed data set, in order to derive a quantitative estimate of the size of the error box (for details, see Pollock et al., 1980). The likelihood is proportional to the probability of obtaining the observations, i.e. the gamma-ray map of the region, given the hypothesis, i.e. the presence of a source of given strength in a given position seen against a background assumed flat. It is noted that in the likelihood method the data are not binned, so that all the directional information from the incoming photons is exploited. The 90% confidence level contour derived with the likelihood method is shown in Fig. 1b. The difference between this and the 6σ confidence contour is not considered significant, in view of the bin size for the latter, and the intrinsic difference between the two methods.

The results of the two methods, cross-correlation and likelihood, are seen to agree as to the coincidence of the source with 3C273. One way to quantise the confidence to be attached to the identification of the γ-ray source with the quasar is given by the evaluation of the probability of chance occurrence at high galactic latitude of an X-ray source of $\gtrsim 3$ UFU (such as $4U1226+02 \equiv 3C273$) in the area of ~ 2.5 square degrees bounded by the 90% contour. From the extragalactic LogN-LogS relation given by Giacconi et al. (1979), i.e. $N(>S) = (7.1 \pm 2.9) \times S^{-1.5}$ sources per steradian at high b^{II}, this probability is (between 0.7 and 1.4) 10^{-3}.

The spectral properties of the γ-ray source were also investigated. The source fluxes were derived from the correlated counts at the position of 3C273 for the three energy intervals 50 to 120, 120 to 230, 230 to 800 MeV. Fig. 2 gives the differential photon spectrum thus obtained, well fitted by the power law:

$$\frac{dN}{dE} = (3.7 \pm 1.4)\, 10^{-6} \left(\frac{E(\mathrm{MeV})}{150}\right)^{-(2.5^{+0.6}_{-0.5})} \quad \text{photons/cm}^2\ \text{s GeV}\,.$$

Finally, the results of the two observations were investigated for possible variability of the flux. The limited statistics available and the global systematic uncertainties inherent to the mission put to $\sim 50\%$ the minimum flux variation detectable, and therefore no evidence of variation is found in the data.

Contemporary X-ray data were available from OSO-8 and HEAO-1 for both COS-B observations (Worrall et al., 1979). The data show good agreement in the source intensities in June 1976 and July 1978, although X-ray variability has been established on the time scale of months (Pounds, 1977; Worrall et al., 1979).

Observations at various other wavelengths are also available at the times of the COS-B γ-ray measurements, as for example the optical and radio data summarized by Bradt et al. (1979), as well as the nearly contemporary IUE observations by Ulrich et al. (1980). However, the comparative study of the temporal behaviour of 3C273 over more than 15 order of magnitude in photon energy is as yet rather inconclusive, and the γ-ray data add but a piece to the puzzle.

3. Discussion

During the second COS-B observation of 3C273, the HEAO-1 satellite performed a pointing observation of the same object. It is interesting in particular to perform a comparison with the results from the A2 (Worrall et al., 1979) and A4 (Primini et al., 1979) experiments, which yielded detailed spectral data, while the identification of the 4U and 2A sources with the quasar was confirmed at the same time with the A3 data (Bradt et al., 1979). If the spectral data in the range 2–60 keV (Worrall et al., 1979) are to be represented by a single power law photon spectrum, its index is $\alpha = 1.41 \pm 0.02$ whereas for those in the range 13–120 keV $\alpha = 1.67 \pm 0.14$ (Primini et al., 1979). Since the measurements were contemporary, it is possible to compare them directly with the COS-B ones, as shown in Fig. 3. A significant change in the spectral slope is apparent, when going from the X to the γ-ray region, beyond the one already present around 30 keV in the A2 and A4 data. The data suggest that the peak luminosity of 3C273 could be expected in the ~MeV range.

Recent data from the High Resolution Imager on the Einstein Observatory (Elvis et al., 1979) bring new evidence on the short term variability of the keV emission from 3C273. In particular, on Dec 14, 1978 a flux variation of 10% was observed on a time scale of the order of 50,000 s coming from a region of 12″ radius centered on the QSO (probably on the position of the radio source 3C273B). If, in the absence of evidence for relativistic expansion effects and/or of beaming of the radiation, one applies the light-travel time argument for the dimension of the varying X-ray source, one can compute, following Jelley (1966), Herterich (1974), and McBreen (1979), the photon-photon optical depth for the 50–800 MeV photons to emerge from the region of high soft-photon density:

$$\tau = r \int_{E_{TH}}^{\infty} \sigma(E) n_x(E) dE ,$$

where: r is the dimension of the X-ray emitting region, $= 1.5\ 10^{15}$ cm, $\sigma(E)$ is the photon-photon interaction cross section, $E_{TH} = \frac{1}{E\gamma} \frac{2(mc^2)^2}{(1-\cos\alpha)}$ is the X-ray threshold energy, α is the angle between the X and γ-photons, $n_x(E)$ is the density of the ambient absorbing photons (= density of X-ray photons per unit energy).

Following Herterich (1974) the $\sigma(E)$ dependence can then be approximated with a rectangular function of height $\sigma_0 = 1.7\ 10^{-25}\ \mathrm{cm}^2$ and width $2.5 E_{TH}$. At the same time $n_x(E)$ can be approximated by its value at $2E_{TH}$.

Then

$$\tau \approx r \cdot \sigma_0 \cdot n_x(2E_{TH}) \cdot 2.5 E_{TH}$$

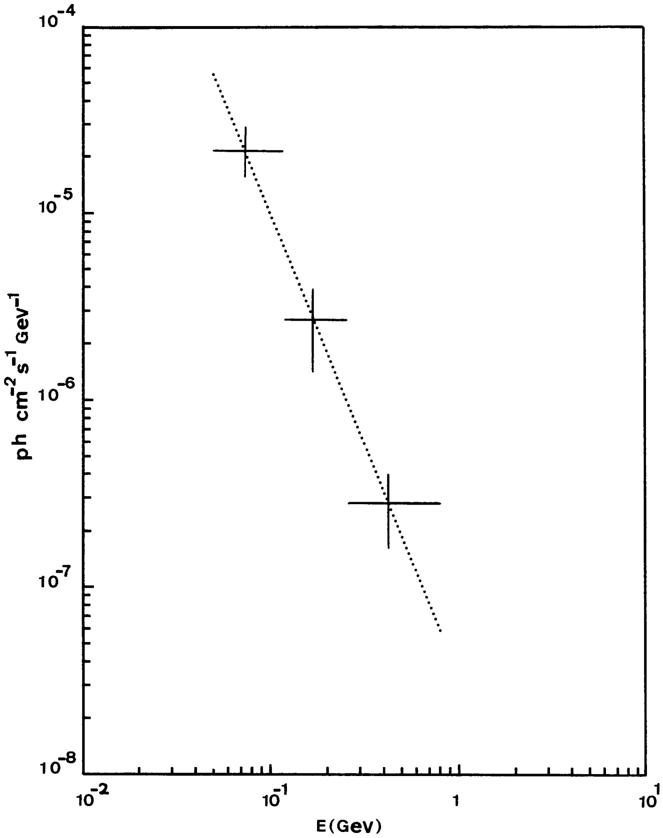

Fig. 2. The differential photon number spectrum obtained by COS-B for the Quasar 3C273. Data from both periods of observation (10 and 32) are included. The best power law fit is also shown:

$$\frac{dN}{dE} = (3.7 \pm 1.4)\, 10^{-6} \left(\frac{E(\mathrm{MeV})}{150}\right)^{-(2.5^{+0.6}_{-0.5})} \ \mathrm{photons/cm^2\ s\ GeV}$$

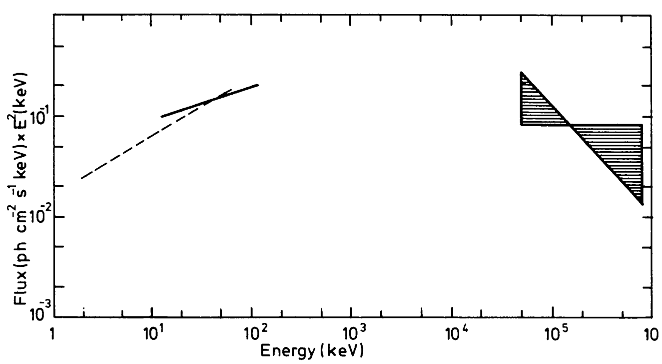

Fig. 3. High energy spectrum of 3C273 including data from HEAO-1, experiment A2 (dotted line) experiment A4 (thick line), and COS-B (shaded area)

Table 2

τ	E (MeV)	E_{TH}(keV)
33.9	800	1.3
31.3	500	2.4
10.4	50	20.0

and

$$n_x(2E_{TH}) = \frac{\Phi(2E_{TH})}{c} \frac{4\pi D^2}{4\pi r^2},$$

where

Φ is the X-ray flux at $E = 2E_{TH}$,

and D is the source distance.

Table 2 gives the optical depth τ for three γ-ray energies and the corresponding threshold X-ray energies. The values of the X-ray flux are taken to be only 10% of the 2–60 keV spectrum of Worrall et al. (1979), being the fraction observed to vary by Elvis et al. (1979).

The assumption is made that 3C273 is at its cosmological redshift distance of 860 Mpc ($z = 0.158$, $H_0 = 55$ km s^{-1} Mpc^{-1}).

It is apparent that the COS-B γ-ray source cannot coincide with the variable Einstein Observatory source, associated with the "nucleus" of the QSO. On the other hand, 3C273 is characterized by a jet, extending in optical some 25″ to the SW (Kron et al., 1972), seen in radio with an elongated structure and the source 3C273A at the end of it (Conway and Stannard, 1975). Very recent Einstein Observatory evidence suggests that the jet is also visible, and resolvable, in soft-X-rays (Henry, 1980). Having excluded the variable X-ray source coincident with 3C273 as a counterpart of the γ-ray source, it is tempting to speculate on an association of γ-ray emission with the jet of the quasar. In this context, the model of Swanenburg (1978) suggests, at least qualitatively, a mechanism for transporting energy out of the nucleus with high energy ($\lesssim 10^{14}$ eV) γ-rays that are somehow beamed.

Another model for the production of high-energy radiation in active nuclei is that of Kafatos (1980, and references therein), based on the Penrose pair production process in the ergosphere of a massive central black hole. Here the energy is extracted from the central source in the form of energetic electrons which then radiate high energy γ-rays in a fan beam of about 40° angle around the equator of the rotating black hole. This beaming is, by itself, not enough to overcome the photon-photon interaction difficulty in the absence of assumptions on the geometry of the soft X-ray emission.

What can be safely said at this stage is that models that account for the γ-ray emission by various order comptonisation of the softer photons close to the "infernal machine" [like the synchrotron self-Compton of Jones (1979) or the "synchrotron boiler" of Tsvetanov and Charugin (1979)] are limited to the production of low-energy ($\sim$MeV) or possibly very high energy ($\gg 10^{10}$ eV) γ-rays.

More detailed knowledge of the γ-ray spectrum of 3C273, and of its variability is required to assess the overall energetics of the QSO. Since the emission of a sizeable fraction of its total energy in γ-rays has been demonstrated for 3C273, it is interesting to speculate on how general a property this may be for QSO's. At the level of sensitivity and coverage of the COS-B mission no other known quasar has so far been detected if one excludes 0241+622, the positional coincidence of which CG 135+1 is very marginal in view of the most recent data (Pollock et al., 1980). While the luminosity functions of QSO's are reasonably well studied in the radio, optical (see e.g. Braccesi et al., 1980) and now also in X-rays (Tananbaum et al., 1979), little evidence exists for relating the power emitted in γ-rays to that in any other wavelength. Considering however the possibility that it is related to the optical and/or X-ray emission in a way similar to that of 3C273, from the luminosity functions and from the mission sensitivity it appears entirely reasonable that only 3C273 be detectable, especially if a beaming mechanism is at work in the γ-ray source. Extending the γ-ray emitting properties to other QSO's out to the maximum observed redshifts (Bignami et al., 1979), can yield an evaluation of the contribution of such objects to the observed isotropic background.

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