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Gamma ray absorption and the distance to Cygnus X-3

M. F. Cawley[1,2] and T. C. Weekes[1]

[1] Harvard-Smithsonian Center For Astrophysics, Fred Lawrence Whipple Observatory, P.O. Box 97, Amado, AZ 85640, USA
[2] Physics Department, Rm 334, University College Dublin, Belfield, Dublin 4, Ireland

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Summary. If the effect of gamma ray absorption by photon-photon pair production is taken into account, the gamma ray luminosity of Cygnus X-3 above 10^{15} eV is significantly increased. This would have the effect of favoring the minimum distance (11.4 kpc) to the source.

Key words: microwave absorption – pair production – gamma rays

Introduction

The importance of photon-photon pair production as a gamma ray absorber was first considered by Nikishov (1962) who calculated the effect for 10^{12} eV gamma rays on optical photons. Gould and Schreder (1966) and Jelley (1966a) showed that the effect should also be considered for 10^{15} eV gamma rays interacting with the microwave blackbody radiation: because of the greater density of microwave photons relative to stellar optical photons within the galaxy, the absorption is proportionally larger and extends beyond the galaxy. At the time there were no known sources of high energy gamma rays so the effect was somewhat academic. There were several air shower experiments which sought to identify gamma rays of energy greater than 10^{14} eV by their low muon-to-electron density: partially as a consequence of the proposed absorption experimental activity in the energy range 10^{14-16} eV came to a virtual standstill.

The detection of ultra high energy gamma rays ($>2\,10^{15}$ eV) from Cygnus X-3 (Samorski and Stamm, 1983) has been reported; this result has been verified by the Haverah Park array (Lloyd-Evans et al., 1983). There have also been reports, but at a lesser significance, of the detection of 10^{15-16} eV gamma rays from the Crab Nebula (Dzikowski et al., 1981; Craig et al., 1981; Hayashida et al., 1981; Boone et al., preprint). Gamma rays of 10^{12} eV had previously been reported from both of these sources (Grindlay, 1972; Jennings et al., 1974; Gupta et al., 1978; Nesphor et al., 1979; Danaher et al., 1981; Lamb et al., 1982; Gibson et al., 1982). These reports prompt a reexamination of the absoprtion effect which may have important consequences for distance estimates to Cygnus X-3.

Gamma ray absorption

The absorption of a gamma ray of energy E_γ by a photon of energy e has a threshold at $E_\gamma e\,(1-\cos\theta)=2(mc^2)^2$ where mc^2 is the rest mass of the electron and θ is the angle between the trajectories of the two photons. The cross-section rises from zero at threshold to a maximum of $10^{-25}\,\mathrm{cm}^2$ just above it.

Send offprint requests to: M. F. Cawley (Dublin address)

a) Absorption at 10^{12} eV

Samorski and Stamm (1983) show that the low energy ($<10^9$ eV) and the ultra high energy ($>10^{15}$ eV) flux measurements of Cygnus X-3 can be fitted by a integral power law of the form

$$N(>E)=(6.4\pm3.6)\,10^{-7}(E/10^9)^{-1.108\pm0.021}\ \mathrm{photons\,cm^{-2}\,s^{-1}}$$

(Fig. 1).

This spectrum predicts a flux of $(3.2\pm2.2)10^{-10}$ photons $\mathrm{cm^{-2}\,s^{-1}}$ for $E=10^{12}$ eV. The observed fluxes (from measurements using the atmospheric Cherenkov technique) at 10^{12} eV are highly variable but have a time averaged value of $3\,10^{-11}$ photons $\mathrm{cm^{-2}\,s^{-1}}$. The observed flux is thus a factor of ten less than that predicted by the above power law; it is possible

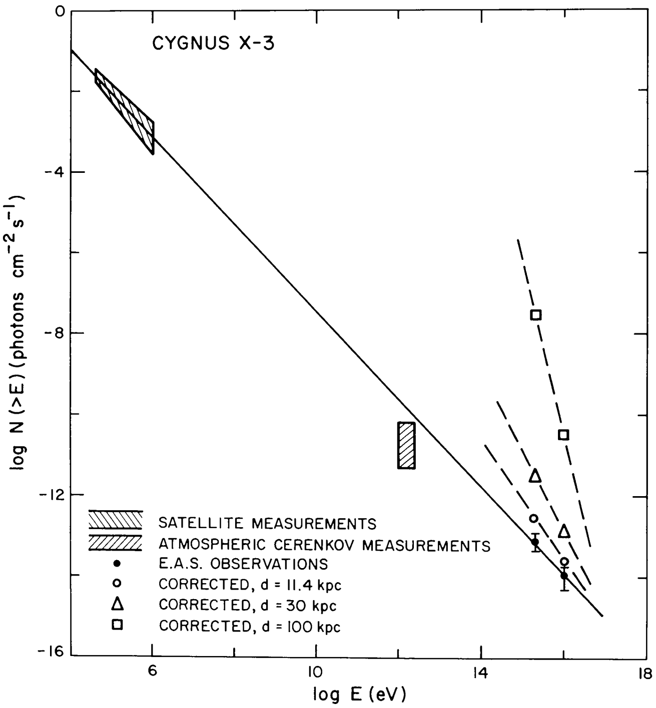

Fig. 1. The observed integral gamma ray spectrum from Cygnus X-3 (Samorski and Stamm, 1983). The solid curve is the best fit to the low and ultra high energy gamma ray points. The dotted curves are the spectra extrapolated from the ultra high energy points taking the microwave absorption into account

that this deficiency can be accounted for by photon-photon pair production by optical photons between the source and the solar system.

The intervening galactic optical photon density is too low (by a factor of 10^3) to account for the "absorption dip" at 10^{12} eV. However the absorption could occur close to the source as previously considered for quasars (Jelley, 1969b) and pulsars (McBreen, 1969). In at least one model (Vestrand and Eichler, 1982) the high energy gamma rays are produced in the atmosphere of the companion star. Although the precise geometry is not defined (and will determine not just the total column density of optical photons traversed but also the angle between the photons and the gamma ray) it is clear that there could be enough photons to account for the apparent absorption. However, as shown below, when microwave absorption of 10^{15} eV gamma rays is taken into account it becomes very unlikely that the entire gamma ray flux emitted from Cygnus X-3 can be fitted by a simple power law.

b) Absorption at 10^{15} eV

Gamma rays of energy 10^{15} eV will undergo photon-photon pair production if the target photons have energy $\sim 10^{-3}$ eV, i.e. microwave photons. Using the method outlined by Gould and Schreder (1966) the absorption probability has been calculated as a function of incident gamma ray energy for a 2.7 K blackbody background. The resulting fractional absorption (as a function of energy and distance) is shown in Fig. 2 where the microwave background is assumed to be universal and isotropic.

The integral gamma ray fluxes measured by Samorski and Stamm (1983) at energies $> 2\,10^{15}$ eV and 10^{16} eV are listed in Table 1 together with the total ultra high energy gamma ray luminosity estimated for a distance of 11.4 kpc. These points are plotted in Fig. 1 together with the extrapolated gamma ray spectrum from lower energies. The 10^{12} eV flux plotted comes from atmospheric Cherenkov experiments which show considerable temporal variations in the measured flux.

Distance to Cygnus X-3

Both the optical (Weekes and Geary, 1982) and X-ray (Gursky et al., 1967) signals show evidence for strong absorption consistent with the location of Cygnus X-3 more than a few kpc away. Early measurements of 21 cm absorption detected absorption features at 3 and 8 kpc but failed to detect any feature at 11 kpc (Lauque et al., 1972). The absorption feature at 11.4 kpc was later detected (Chu and Bieging, 1973; Lauque et al., 1973; Dickey, 1983). This is the distance to the edge of the galactic plane in that direction. There is no upper limit to the distance other than energy considerations: Geldzahler et al. (1983) have considered the possibility that the source might be extragalactic. Similarity with galactic X-ray binaries makes this somewhat unlikely; however Cygnus X-3 differs in several fundamentals from standard X-ray binaries.

Because of the distance uncertainty we have tabulated the high energy fluxes for distance of 11.4, 30, and 100 kpc where corrections have been made for absorption by photon-photon pair production. Even at the minimum distance of 11.4 kpc the absorption is considerable. The corrected fluxes are plotted in Fig. 1 without error bars; they can no longer be fitted by the extrapolated lower energy spectrum. As the distance increases the spectrum steepens sharply. Estimates of the energy emitted in the 10^{15-16} eV decade are also listed in Table 2 as a function of distance. Note that the proportion of energy emitted in ultra high energy gamma rays relative to the X-ray luminosity ($L_X \sim 10^{38}$ erg s^{-1} at 10 kpc) increases with distance: since this is large even at the minimum distance, it becomes the dominant energy channel if the distance is > 30 kpc.

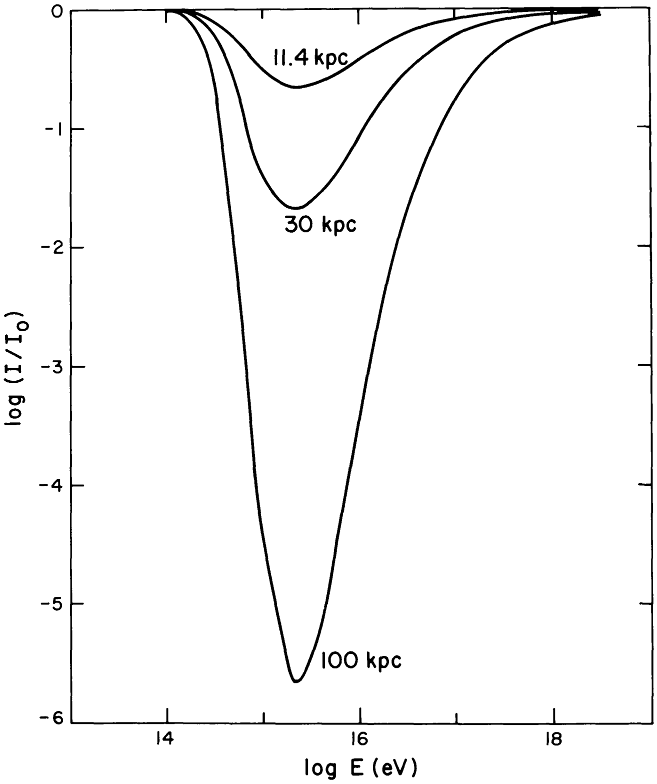

Fig. 2. The fractional absorption by the 2.7 K blackbody radiation as a function of gamma ray energy for three possible source distances

Table 1. Measured and corrected fluxes

Gamma ray energy (eV)	Measured flux γ cm^{-2} s^{-1}	Corrected flux		
		$d = 11.4$ kpc γ cm^{-2} s^{-1}	$d = 30$ kpc γ cm^{-2} s^{-1}	$d = 100$ kpc γ cm^{-2} s^{-1}
$> 2\,10^{15}$	$7.4 \pm 3.2\,10^{-14}$	$3\,10^{-13}$	$3\,10^{-12}$	$3\,10^{-8}$
$> 10^{16}$	$1.1 \pm 0.6\,10^{-14}$	$2.5\,10^{-14}$	$1.2\,10^{-13}$	$3.6\,10^{-11}$

The existing models for Cygnus X-3 do not predict the emission of 10^{16} eV gamma rays. Even for a comparatively young pulsar the upper limit to the energy emitted is expected to be less than 10^{16} eV. Because there is no known source with such a high proportion of ultra high energy gamma rays, the minimum distance, implying the smallest proportion, is favored. These larger distances would also imply superluminal expansion velocities (Geldzahler et al., 1983).

Table 2. Total and relative gamma ray luminosity

Distance (kpc)	10	11.4	30	100
L_γ (erg s^{-1})	$6\,10^{36}$	$2\,10^{37}$	$9\,10^{38}$	$4\,10^{43}$
L_γ/L_X	0.6	2	13	$4.7\,10^{4}$

Discussion

The correction of the detected fluxes of Cygnus X-3 for photon-photon absorption has the following consequences:

(i) the entire gamma ray spectrum from 10^6 to 10^{16} eV can no longer be fitted by a simple power law,

(ii) the distance to the source is unlikely to be much greater than 11.4 kpc,

(iii) more energy may be radiated in the 10^{15-16} eV energy band than in any other decade.

If the high energy spectrum of Cygnus X-3 can be better determined it may be possible to measure the absorption feature described above assuming a simple power law emission spectrum. The measurement of such a feature would:

(i) give a unique measurement of the distance to the source,

(ii) verify the photon-photon absorption process (Gould, preprint),

(iii) confirm the extent of the 2.7 K blackbody field (Gould, preprint). The detection of one such source of 10^{16} eV gamma rays (and possibly a second, the Crab Nebula) implies the existence of others. If the detection technique can be refined, then it may be possible to detect more distant galactic point sources at higher energies. If these sources are also detected in the atmospheric Cherenkov energy range (10^{11-14} eV) then it may be possible to measure the very strong microwave absorption feature. *This would be a unique and independent measurement of the distance to the source.* Time variations and uncertainty about the emission spectrum would complicate the interpretation but the results are sufficiently important to merit a renewed search for point source anisotropies at high energies.

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References

Chu, K.W., Bieging, J.H.: 1973, *Astrophys. J. Letters* **179**, L 21
Craig, M.A.B., Orford, K.J., Turver, K.E., Weekes, T.C.: 1981, *Proc. 17th Intern. Cosmic Ray Conf.* **1**, 3
Danaher, S., Fegan, D.J., Porter, N.A., Weekes, T.C.: 1981, *Nature* **289**, 568
Dickey, J.M.: 1983, *Astrophys. J. Letters* **273**, L 71
Dzikowski, T., Gawin, J., Grochalska, B., Wasilewski, A., Wdowczyk, J.: 1981, *Proc. 17th Intern. Cosmic Ray Conf.* **1**, 8
Geldzahler, B.J., Johnston, K.J., Spencer, J.H., Kelpczynski, W.J., Josties, F.J., Angerhofer, P.E., Florkowski, D.R., McCarthy, D.D., Matsakis, D.N., Hjellming, R.M.: 1983, *Astrophys. J. Letters* **273**, L 65
Gibson, A.I., Harrison, A.B., Kirkman, I.W., Lotts, A.P., Macrae, J.H., Orford, K.J., Turver, K.E., Walmsley, M.: 1982, *Proc. Int. Workshop on Very High Energy Gamma Ray Astronomy*, Ootacamund, India, p. 97
Gould, R.J., Schreder, G.: 1966, *Phys. Rev. Letters* **16**, 252
Grindlay, J.E.: 1972, *Astrophys. J. Letters* **174**, L 9
Gupta, S.K., Ramana Murthy, P.V., Sreekantan, B.V., Tonwar, S.C.: 1978, *Astrophys. J.* **221**, 268
Gursky, H., Gorenstein, P., Giacconi, R.: 1967, *Astrophys. J.* **150**, L 75
Hayashida, N., Ishikawa, F., Kamata, K., Kifune, T., Nagano, M., Tan, Y.H.: 1981, *Proc. 17th Intern. Cosmic Ray Conf.* **9**, 9
Jelley, J.V.: 1966a, *Phys. Rev. Letters* **16**, 479
Jelley, J.V.: 1966b, *Nature* **211**, 472
Jennings, D.M., White, G., Porter, N.A., O'Mongain, E., Fegan, D.J., White, J.: 1974, *Nuovo Cimento* **20**, 71
Lamb, R.C., Godfrey, C.P., Wheaton, W.A., Tumer, T.: 1982, *Nature* **296**, 543
Lauque, R., Lequeux, J., Nguyen-Quang-Rieu: 1972, *Nature Phys. Sci.* **239**, 119
Lauque, R., Lequeux, J., Nguyen-Quang-Rieu: 1973, *Nature Phys. Sci.* **241**, 94
Lloyd-Evans, J., Coy, R.N., Lambert, A., Lapikens, J., Patel, M., Reid, R.J.O., Watson, A.A.: 1983, *Nature* **305**, 784
McBreen, B.: 1969, *Nature* **224**, 893
Neshpor, Y.I., Stepanian, A.A., Fomin, V.P., Gerasimov, S.A., Vladimirsky, B.M., Ziskin, Y.L.: 1979, *Astrophys. Space Sci.* **61**, 349
Nikishov, A.I.: 1962, *Soviet Phys.* – JETP **14**, 393
Samorski, M., Stamm, W.: 1983, *Astrophys. J. Letters* **268**, L 17
Vestrand, W.T., Eichler, D.: 1982, *Astrophys. J.* **261**, 251
Weekes, T.C., Geary, J.C.: 1982, *Publ. Astron. Soc. Pacific* **94**, 708