

Cygnus X-3 Revisited: 10 Years of Muon and Radio Observations

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Abstract

The Soudan 2 deep underground tracking calorimeter has recorded cosmic ray muon tracks from the direction of the galactic x-ray binary Cygnus X-3 on most transits during the interval 1989-1998. We analyze these events in the context of previous reports of Cygnus X-3-related muon flux during major radio flares of that source. We find some evidence for excess flux during a small number of transits coincident with major radio flares. We also find an indication that these events may be distributed around the source with a Gaussian point spread function with $\sigma = 1.3^\circ$, larger than the instrumental angular spread of $\leq 0.3^\circ$, verified by observation of the shadow of the moon.

1 Introduction

Cygnus X-3 is a galactic binary star system known to emit highly variable fluxes of radio, infrared and x-ray radiation (Bonnet-Bidaud, 1988 and Nagle, 1988). Episodically, radio fluxes from Cygnus X-3 vary over three orders of magnitude within a few days (Waltman, 1994). However, such major flares are infrequent, occurring on average every several years. The best current understanding of Cygnus X-3 is that it is one of several known "microquasars," non-thermal star systems in our galaxy that from time to time emit strong radio flares associated with relativistic jets pointed towards the earth. Microquasars are smaller versions of extragalactic quasars, which also produce highly collimated radiation through relativistic jets.

Over a number of years, cosmic ray air shower and deep underground muon detectors have reported both positive and negative observations of TeV or above quanta associated with Cygnus X-3. Several observations have identified high energy muons as secondaries in Cygnus X-3-related events. At TeV energies, only stable, neutral particles can travel the > 8 kpc distance from Cygnus X-3 to the earth along trajectories which point back to the source. The known stable, neutral particles—photons and neutrinos—have only small probabilities for producing detectable muons. Thus, observation of TeV muons associated with Cygnus X-3 requires either exotic interactions of known primaries, exotic primaries or very large fluxes of neutrinos or photons. The lack of a conventional physical model and the sometimes contradictory reports of transient fluxes have decreased recent interest in Cygnus X-3 as a TeV or higher energy source. For the past 5 years, there have been no published reports concerning such particles from Cygnus X-3.

The last published, positive Cygnus X-3 muon observation reported excess deep underground muons observed by the Soudan 2 detector (Thomson, 1991: Paper I and Thomson, 1992) apparently in association with

that system’s January 1991 major radio flare. Other nearly simultaneous observations observed no unexpected effects (Becker-Szendy, 1993). There are several reasons to now re-examine the Soudan 2 observations of muons from the direction of Cygnus X-3. (1) Paper I was based on 2.1 years of data, during an interval when the Soudan 2 detector was under construction. Soudan 2 has now recorded 10 years of data during mostly stable operation. (2) The analysis for Paper I used a conservative estimate of the angular resolution and pointing accuracy of the Soudan 2 detector. These parameters have now been measured by observation of the cosmic ray shadow of the moon. The actual values (and 1991 estimates) for angular resolution and pointing accuracy are: gaussian with $\sigma \leq 0.3^\circ$ (1.0°) and $\leq 0.15^\circ$ (0.5°). (3) Detailed radio flux measurements for Cygnus X-3 are now available for most days during the entire 10-year Soudan 2 observation interval.

2 Data Collection and Analysis

The Soudan 2 detector is a deep underground iron tracking calorimeter designed to search for proton decay. The detector and the event collection and track analysis procedures are described elsewhere (Allison, 1996). The data sample reported here consists of 3.6×10^7 events which have passed run and event cuts, both intended to identify a high-purity, high-resolution muon track sample. The backgrounds or expected numbers of events in the absence of a source reported here have been determined by randomly pairing, month-by-month, arrival times of real events with track directions in detector coordinates of other real events. This analysis uses a $100 \times$ background sample.

As in Paper I, we focus first on real and background events which point within 2° of the direction of Cygnus X-3 (J2000 $\alpha = 308.10^\circ$, $\delta = 40.96^\circ$). From the radio data, we have identified 3 major and 7 intermediate radio flares of Cygnus X-3 during the entire 1989-1998 interval as listed in the table below. The entire data sample includes 3,046 Cygnus X-3 transits during which the background calculation indicates that 2 or more events are expected from the source direction. Of these transits, 139 are coincident with major radio flares, 105 with intermediate radio flares and 2,802 with neither of these categories of radio flares. For each transit, we have determined the Poisson probability $P(\geq n, \mu)$ that n or more muons are observed (where n is the number of muons that were observed) during a transit in which μ muons are expected. Fig. 1(a) shows a semi-log histogram of the number of transits N vs. $-\log_{10} P(\geq n, \mu)$ for the major flare, intermediate flare and neither flare transits. The figure also shows Monte Carlo calculations of the same distributions, assuming Poisson statistics.

Table 1. Major and Intermediate Radio Flares of Cygnus X-3: 1989 to 1998.

| Type | Start Date | End Date | Peak 3 GHz Flux (Jy) | Peak 8 GHz Flux (Jy) |
|--------------|------------|-----------|----------------------|----------------------|
| Major | 1 Jun 89 | 14 Aug 89 | 15.4 | 15.8 |
| Intermediate | 11 Aug 90 | 31 Aug 90 | 7.8 | 7.2 |
| Intermediate | 1 Oct 90 | 22 Oct 90 | 9.3 | 9.0 |
| Major | 18 Jan 91 | 19 Mar 91 | 11.9 | 13.9 |
| Intermediate | 19 Jun 91 | 30 Jun 91 | 4.5 | 3.6 |
| Major | 24 Jul 91 | 29 Aug 91 | 16.4 | 13.1 |
| Intermediate | 1 Sep 92 | 11 Sep 92 | 3.7 | 3.7 |
| Intermediate | 20 Feb 94 | 11 Mar 94 | 4.8 | 4.6 |
| Intermediate | 1 Feb 97 | 16 Feb 97 | 9.2 | 8.4 |
| Intermediate | 10 Jun 97 | 25 Jun 97 | 3.7 | 3.1 |

The distributions in Fig. 1(a) for the “Intermediate Flare” and “No Flare” transits appear consistent with expectations of Poisson statistics. However, as suggested in Paper I, there are transits in the “Major Flare” sample with an excess of observed events, including the two specific transits cited in that paper. For example, the “Major Flare” graph in Fig. 1(a) shows 6 transits with $-\log_{10} P(\geq n, \mu) \geq 2$ with 0.89 such transits expected (chance probability $\leq 3.2 \times 10^{-4}$) and 10 transits with $-\log_{10} P(\geq n, \mu) \geq 1.5$ with 3.1 such

transits expected (chance probability $\leq 1.4 \times 10^{-3}$). Of these 10 transits, 3 occurred during the June 1989 flare, 4 (including the two cited in Paper 1) occurred during the January 1991 flare and 3 occurred during the August 1991 flare (see Table 2). The numbers of events listed in the table for the transits discussed in Paper I differ somewhat from those given in that paper because the current analysis uses a modified reconstruction algorithm and tighter cuts in order to improve the detector angular resolution and reduce reconstruction errors.

Table 2. Transits with $-\log_{10} P(\geq n, \mu) \geq 1.5$.

| Date | Observed Events | Expected Events | $-\log_{10} P(\geq n, \mu)$ |
|-----------|-----------------|-----------------|-----------------------------|
| 5 Jun 89 | 9 | 2.53 | 2.91 |
| 18 Aug 91 | 17 | 7.62 | 2.64 |
| 24 Aug 91 | 16 | 7.45 | 2.36 |
| 24 Jan 91 | 13 | 5.62 | 2.28 |
| 16 Aug 91 | 15 | 7.15 | 2.16 |
| 19 Jun 89 | 8 | 2.79 | 2.10 |
| 10 Mar 91 | 12 | 5.61 | 1.89 |
| 19 Feb 91 | 11 | 5.16 | 1.77 |
| 15 Jun 89 | 7 | 2.75 | 1.65 |
| 21 Jan 91 | 10 | 4.97 | 1.51 |

Although a 2° half-angle cone has been used to select the transits discussed above, the $\leq 0.3^\circ$ angular resolution of the Soudan 2 detector should indicate pointing towards the source, if an event excess associated with major radio flares is a real effect. Fig. 1(b) shows an angular distribution for all 4,303 muon events observed within 5° of Cygnus X-3 during all transits occurring during the three major radio flares (not just the 10 transits listed in Table 2). A goodness-of-fit test between the observed distribution in Fig. 1(b) and the expected (or background) distribution in the absence of a source (not shown) yields $\chi^2 = 37.4$ for 25 df (chance probability = 0.05). The fit shown in Fig. 1(b) adds a Gaussian source (or sink) term to the expected “no-source” distribution with the amplitude of the Gaussian fixed by the total number of excess observed events. A χ^2 minimization then yields $\sigma = 1.3^{+0.5^\circ}_{-0.4^\circ}$. The chance probability of the χ^2 improvement resulting from the fit is 0.01. The data in Fig. 1(b) show no evidence for a source with the detector angular resolution of $\sigma \leq 0.3^\circ$. Also, plots similar to Fig. 1(b) for data recorded during the “Intermediate Flare” and “No Flare” intervals show no evidence for any source term in their angular distributions.

3 Conclusions

The question of whether VHE or UHE quanta are associated with Cygnus X-3 may remain unresolved for some period of time. We have shown here evidence for an excess of directional events associated with major radio flares of Cygnus X-3. However, the absence of a well-understood physical mechanism, the *post hoc* nature of the analysis and the small number of events leading to modest statistical confidence levels diminish the impact of these observations. What is required to solidify any conclusions about high energy quanta from Cygnus X-3 are predictable observations. Yet, despite daily monitoring, no major Cygnus X-3 radio flares have been observed since 1991, making predictions about muons during major radio flares untestable. It is not known if or when such flares might be observed in the future. Thus, searches for deep underground muon sources may need to be directed elsewhere, if past observations are ever to be understood.

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References

- Allison, W.W.M., *et al.*, 1996 Nucl. Inst. and Meth. **A376**, 377 and **A381**, 385.
 Becker-Szendy, R., *et al.*, Phys. Rev. **D10**, 4203 (1993).

Bonnet-Bidaud, J.M. and G. Chardin, 1988 Phys. Rep. **170**, 326.
 Nagle, D.E., T.K. Gaisser and R.J. Protheroe, 1988 Ann. Rev. Nucl. Part. Sci., 609.
 Waltman, E.B., *et al.*, 1994 Astronom. J. **112**, 2690 (1996), **110**, 290 (1995), **108**, 179.
 Thomson, M.A., *et al.*, Phys. Lett. **B269**, 220 (1991).
 Thomson, M.A., D. Phil. Thesis, Oxford University, 1992.

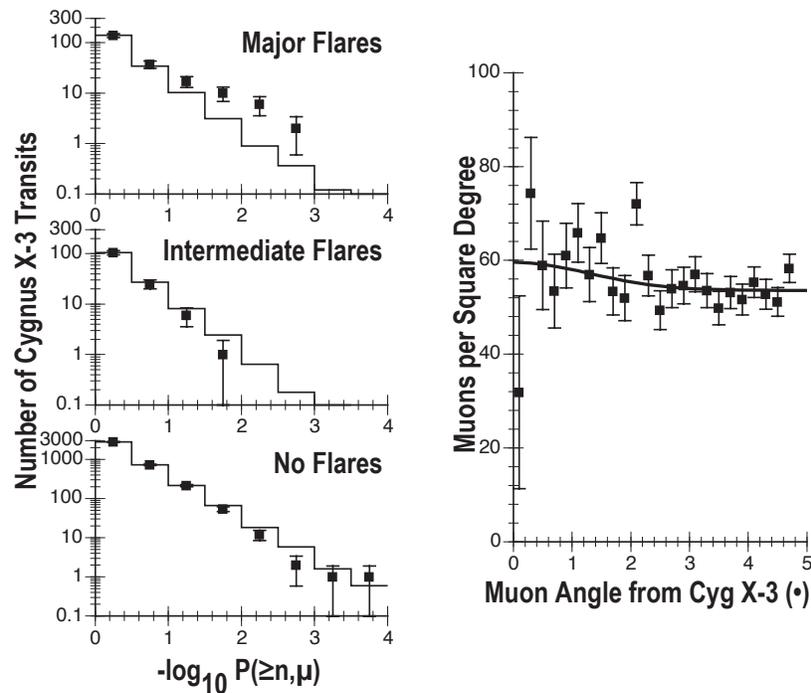


Figure 1: (a) (left) The observed numbers of transits (points) vs. $-\log_{10} P(\geq n, \mu)$ for “Major Flare”, “Intermediate Flare” and “No Flare” intervals described in the text. The solid lines show the expected distributions from a simulation that assumes Poisson statistics. (b) (right) The number of muons per square degree vs. the angle in degrees between the muon track and Cygnus X-3 for events during major radio flares. The solid line is the Gaussian fit described in the text with $\sigma = 1.3^\circ$.