# A New Tev Binary: The Discovery of an Orbital Period in HESS J0632+057


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## Abstract

**HESS J0632+057 is a variable, point-like source of Very High Energy (> 100 GeV) gamma-rays located in the Galactic plane. It is positionally coincident with a Be star, it is a variable radio and X-ray source, has a hard X-ray spectrum, and has low radio flux. These properties suggest that the object may be a member of the rare class of TeV/X-ray binary systems. The definitive confirmation of this would be the detection of a periodic orbital modulation of the flux at any wavelength. We have obtained Swift X-ray telescope observations of the source from MJD 54857 to 55647 (Jan. 2009 - Mar. 2011) to test the hypothesis that HESS J0632+057 is an X-ray/TeV binary. We show that these data exhibit flux modulation with a period of 320 ± 5 days, and we evaluate the significance of this period by calculating the null hypothesis probability, allowing for stochastic flaring. This periodicity establishes the binary nature of HESS J0632+057.**

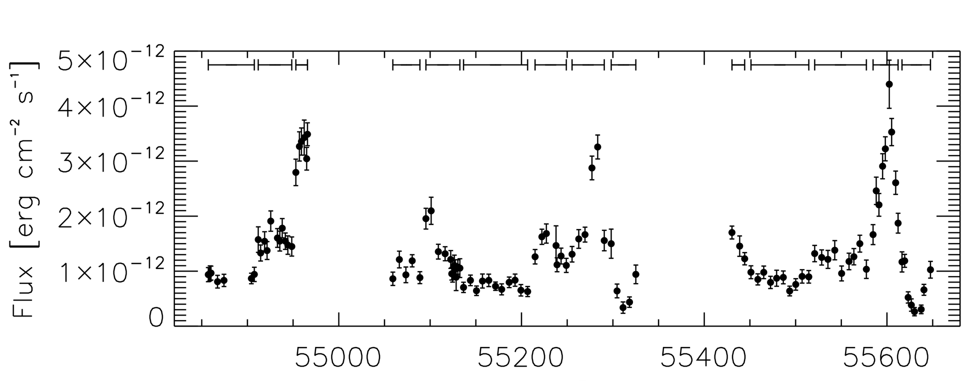

## Introduction

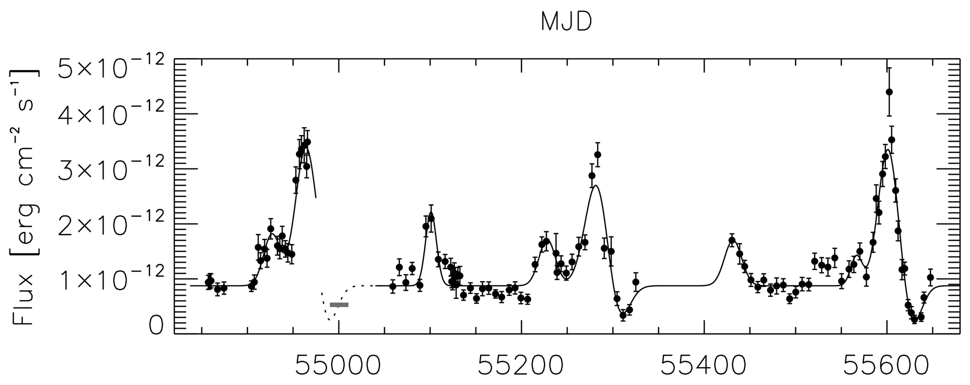
- HESS J0632+057 detected; suggested TeV binary (Aharonian et al. 2007)
  - Coincident with EGRET UnID 3EG J0634+0521
  - Not identified in Fermi LAT point source catalog
  - Coincident with MWC 148 (B0pe star)
- XMM observes source on 2007 September 17 (Hinton et al. 2009) resulting in the identification of point source XMMU J063259.3+054801, which is positionally coincident with both MWC 148 and HESS J0632+057, and within the 99% error circle of 1RXS J063258.3+054857. $\Gamma = 1.26 \pm 0.04$
- Swift begins monitoring of XMMU J063259.3+054801 on 2009 January 26 (Falcone et al. 2010)
- VERITAS observes HESS J0632+057 above 1 TeV during December 2006 - January 2007 and December 2008 - January 2009 (Acciari et al. 2009b) yielding flux upper limits well below the values published by HESS. Together, the VERITAS and HESS observations provide evidence for variability of the gamma-ray flux on time scales of months. More recently, both VERITAS and MAGIC have detected elevated TeV gamma-ray emission (Ong et al. 2011; Mariotti et al. 2011) during the time period of elevated X-ray flux reported by Falcone et al. (2011) in February 2011.
- 5 GHz observations show significant variability on month-long time scales around a mean flux of 0.3 mJy (Skilton et al. 2009), however no periodic variability could be detected in these data. This radio flux is much lower than the typical radio flux expected from a TeV blazar, making such a potential interpretation improbable.

The point-like nature of the detected TeV source, the excellent positional coincidence with MWC 148, the location on the Galactic plane with a low radio flux, the X-ray binary-like spectral index, and the variable X-ray and gamma-ray emission are all facts that argue in favor of an X-ray binary in association with MWC 148. The most direct way to test this binary hypothesis is to search for periodic emission signatures. Here, we report on recent monitoring data taken with Swift-XRT.

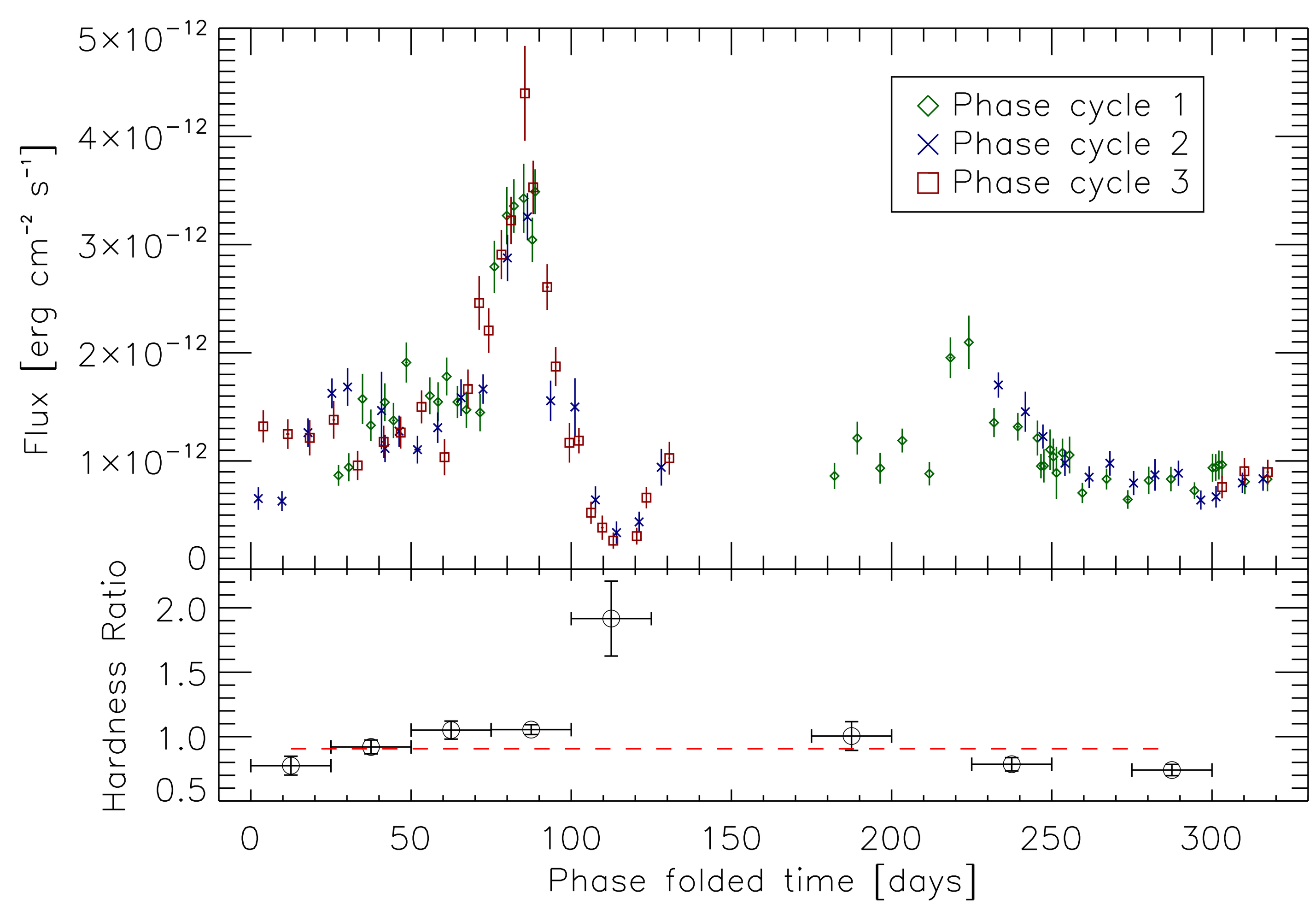
## Observations

The X-ray Telescope (XRT) on the Swift observatory was used to obtain 110 observations in the 0.3-10 keV energy band. The typical observation duration was ~5 ks with ~1 week spacing between most observations. There were extended periods with no observations due to the source's close proximity to the Sun. The total Swift-XRT data set includes 463 ks of observations, extending from 2009 January 26 (MJD 54857.1) to 2011 March 27 (MJD 55647.6), representing a baseline of T=790.5 days. All observations were obtained in photon counting (PC) mode.




## Folded Light Curve




## Significance of the Period

To better estimate the significance of the 320 day periodicity, we performed Monte-Carlo simulations. By simulating many light curves with flare features similar in size and occurrence frequency to those seen in the observed light curve, we can estimate the probability that the light curve is generated by a source that exhibits the observed flaring pattern every 320 days, and not by a source that flares randomly in time.

During the entire period of Swift observations when peaks and dips could have been observed, we observed 3 large peaks, 3 small precursor peaks, 2 dips, and 2 small mid-phase peaks. To generate the appropriate number of features of each type, we sample a random deviate from a Poisson distribution corresponding to the calculated rate of occurrence. The shape of each feature is then created with a Gaussian peak of height and width generated by selecting a random deviate from a normal distribution with mean and variance measured in the corresponding feature type in the observed light curve. The mean position of each peak is generated by selecting a random deviate from a probability distribution that is uniform across the observation baseline (MJD 54857 to MJD 54647). The peaks and dips are then combined with the best fit value for the quiescent emission derived from data. The final simulated light curve is generated by sampling the model of superposed Gaussian peaks at the bin-center-times when Swift observed HESS J0632+057.

We then calculate the $\chi^2$ between the simulated light curve and the model that best fit the observed data. The fraction of simulated light curves with calculated $\chi^2$ less than that of the data represents the probability of generating the observed light curve with a source that is stochastically flaring (with flares having the observed size and rate of occurrence). In this way, we created $10^9$ simulated light curves with randomly distributed flares and dips, none of which resulted in a $\chi^2$ value less than that of the actual light curve, relative to the model light curve fit. Therefore, we find the false alarm probability for finding this periodic light curve from similar-sized stochastic flaring to be $P < 1 \times 10^{-9}$.

## Discussion

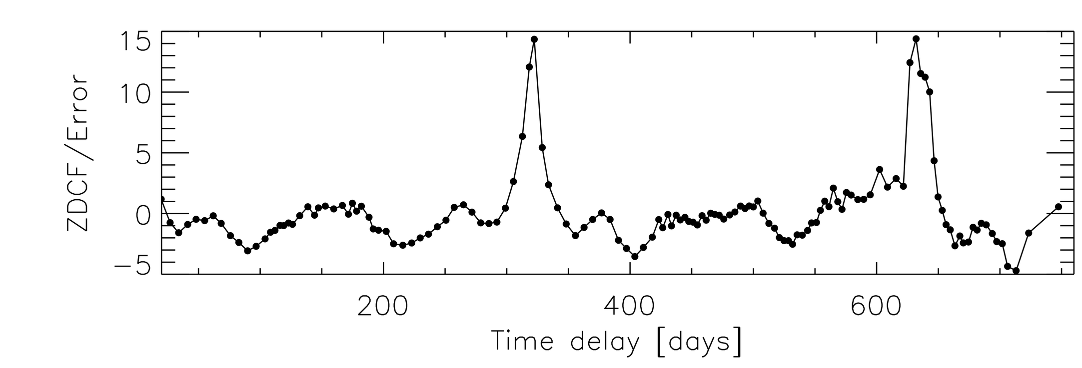
The folded light curve (*above*) shows that the hardness does not vary significantly throughout most of the orbit, but it **does reach a significant maximum when the light curve exhibits a dip feature**. A constant line fit of the hardness data (red dashed line) results in a $\chi^2$ of 55.4 (with 7 dof), which shows that spectral variability is present, particularly during the flux dip. This is consistent with the harder photon index measured by Hinton et al. (2009) at a time corresponding to a dip feature in the light curve, phased forward by two periods (gray shaded box in the light curve). This hardening of the X-ray spectrum during a flux decrease may be due to:

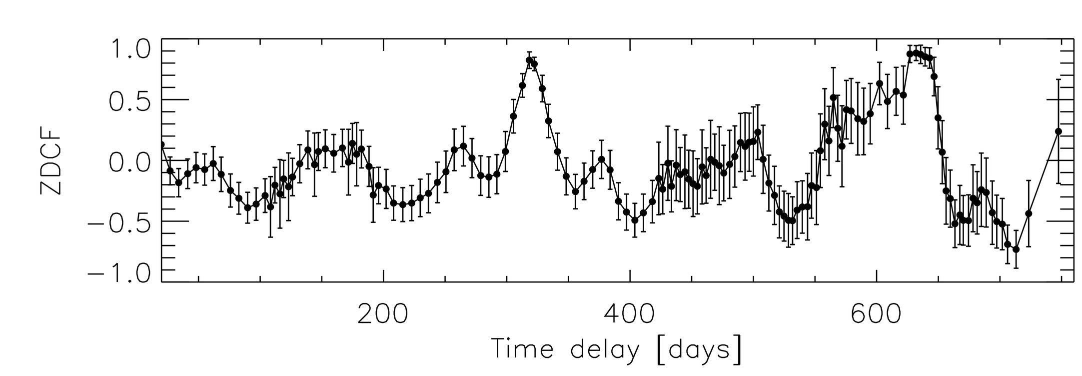
- Increased absorption of the soft X-rays in the source region. This argues for a geometry of the binary system that allows the Be star and/or its equatorial disk to pass between the X-ray emission region and our line-of-sight and also implies that the binary orbit is highly inclined and that the emission region is small enough to be eclipsed. However, this would likely be associated with increased $N_H$, which is not observed in these data, making this interpretation less likely.
- Orbital modulation of acceleration site parameters such as electron injection energies and cooling timescales.

In addition to the flux dip feature discussed above, the dominant features of the periodic phased X-ray light curve are a large flux peak with a factor of 5-6 flux increase over quiescent flux and a moderate flux peak with a factor of ~2.5 flux increase over quiescent flux. These peaks are separated in time by about one half period and each feature lasts ~4 weeks. The recent increase in TeV flux reported by Ong et al. (2011) and Mariotti et al. (2011) coincides with the time of the recent large X-ray peak, which could imply related mechanisms such as synchrotron and inverse Compton emission. By analogy with known X-ray binaries, it is reasonable to speculate that the peaks are periastron and apastron, but it is not clear which is which. If the spectral hardening discussed above is due to absorption from the Be star and the surrounding region, then the geometry would be most easily solved if the large flux peak were due to periastron passage. However, it is worth noting that studies to-date have not found evidence for optical radial velocity shifts in the optical counterpart MWC 148 (Aragona et al. 2010; Casares et al. 2011).

## Autocorrelation

An autocorrelation analysis is often used as a test for repeating patterns in astronomical time series, as it requires no prior assumptions about the light curve profile (e.g. Ciprini et al. (2007); Xie et al. (2008)). The Discrete Auto-Correlation Function (DACF), in particular, can be used to study the level of auto-correlation in unevenly sampled datasets without any interpolation or addition of artificial data points (Edelson & Krolik 1988). The figure (*below*) shows the result of applying the z-transformed DACF (Alexander 1997) to the Swift-XRT dataset. We show both the autocorrelation value, and the autocorrelation divided by its error, which provides an estimate of the significance of the autocorrelation measurement. A clear peak is visible at a time lag of ~320 days, as well as the expected peak at twice this period.




## Peak Fitting

Peak fitting is a simple and robust method for measuring the period of variability in data, such as these, where modulation is readily characterized by isolated peaks of enhanced and suppressed emission superimposed upon a quiescent state. We therefore model the light curve with a sum of 10 Gaussians (one for each peak feature) and a constant (for the quiescent emission). This results in 31 free parameters. To obtain the best fit value for the parameters we perform a chi-square minimization between the model and data. The final fit is shown as a solid line (*below left*) and resulted in a $\chi^2$ value of 207.5 for 79 degrees of freedom. While the entire light curve is not ideally fit by this model, it provides a reasonable characterization of the variability and, more importantly, allows us to characterize the timing of the primary features in the light curve. The large $\chi^2$ is evidence that additional, small-scale variability is present in the light curve.

We propose that the large peaks (MJD 54966.2, 55283.3, and 55601.3) and the dips (MJD 55303.4 and 55630.0) most accurately characterize periodic behavior in the light curve. The small precursor peaks that precede each large peak are unsuitable for measuring the period because they are observed to have variable shape, position (with respect to the large peaks), and height and because their significance above quiescence is small. The small mid- phase peaks are also unsuitable for measuring the period because the second peak, centered at MJD 55431.8, is poorly sampled, yielding an unreliable peak position estimate. Averaging the separations between peak centers, using large peaks and dips, we calculate a period of 320 days. We conservatively estimate the error to be ±5 days, the approximate average sampling rate during the large peaks and dips. Using this period, we have plotted the phase- folded light curve (*above center*). This shows a strong similarity between modulation observed during different phases, particularly during the large peaks and dips.

## Conclusions

- We have detected a 320 ± 5 day period in the 0.3-10 keV light curve of the unidentified TeV object HESS J0632+057.
- The observed periodicity has been shown to be significant by estimating the chance probability that the observed light curve periodicity is due to stochastic flaring of the source, resulting in a false alarm probability of $P < 1 \times 10^{-9}$.
- This implies a binary nature of HESS J0632+057, making it the fourth confirmed TeV binary (there are now 5 confirmed gamma-ray binaries, if one includes the recent announcement by Corbet et al. (2011) of GeV emission from 1FGL J1018.6-5856). The 320 ± 5 day period also makes it one of the longest period Be star TeV/X-ray binaries.

For more details, see the recently submitted paper on these results: Bongiorno, S.D., Falcone, A.D., Stroh, M., Holder, J., Skilton, J.L., et al. 'A New TeV Binary: The Discovery of an Orbital Period in HESS J0632+057', ApJL, submitted (arXiV:1104.4519)

## References


Acciari, V.A. et al. 2008, ApJ, 679, 1427
Acciari, V.A. et al. 2009, ApJ, 700, 1034
Acciari, V.A. et al. 2009b, ApJ, 698, L94
Aharonian F., et al. 2007, A&A, 469, L1
Aharonian et al. 2005a, Science, 309, 746
Aharonian et al. 2005b, A&A, 442, 1
Alexander, T. 1997, in Astronomical Time Series, Eds. D. Maoz, A. Sternberg, E.M. Leibowitz (Dordrecht: Kluwer), p. 163
Aragona, C., McSwain,V., & De Becker. 2010, A&A, 724, 306
Casares, J., Ribo, M., Parades, J.M., et al. 2011, ATEL#3209
Ciprini, S., Takalo, L. O., Tosti, G., Raiteri, C. M., et al. 2007, A&A, 467, 465
Corbet, R. H. D., Cheung, C. C., Kerr, M., Dubois, R., & Donato. 2011, ATEL#3221
Edelson, R. A. & Krolik, J. H. 1988, ApJ, 333, 646
Falcone, A.D., Bongiorno, S., Stroh, M., Holder, J. 2011, ATEL#3152
Falcone, A.D., et al. 2010, ApJ, 708, L52
Hinton, J., Skilton, J., Funk, S., et al. 2009, ApJ, 690, 101
Mariotti, M., et al. 2011, ATEL#3161
Ong, R., et al. 2011, ATEL#3153
Skilton, J., et al. 2009, MNRAS, 399, 317
Smith, A., Kaaret, P., Holder, J., Falcone, A., Maier, G., et al. 2009, ApJ, 693, 1621
Xie, G. Z., Yi, T. F., Li, H. Z., Zhou, S. B., & Chen, L. E. 2008, AJ, 135, 2212



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