An Outburst of GeV Gamma-Ray Emission from Centaurus X-3

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ABSTRACT

We present *CGRO/EGRET* measurements of an outburst of >100 MeV gamma-ray emission from the massive X-ray binary system Centaurus X-3 that occurred during an interval of rapid spindown by the x-ray pulsar. For the October 1994 outburst, the phase-averaged 30 MeV-10 GeV emission is best fit by a power law with index $\alpha = 1.81 \pm 0.37$ and an integral flux above 100 MeV of $9.2(\pm 2.3) \times 10^{-7}$ photons cm^{-2} s^{-1} corresponding to a phase-averaged luminosity in GeV gamma-rays of $\sim 5 \times 10^{36}$ erg s^{-1}. Our phase analysis, employing the contemporaneous x-ray pulse observations by *CGRO/BATSE*, indicates modulation of the gamma-ray emission at the pulsar spin frequency with a significance level higher than 99.5%. Straightforward interpretation of the *EGRET* measurements requires at least sporadic acceleration of GeV particles within the Cen X-3 binary system. The observations also suggest that galactic x-ray binary systems may constitute a class of highly variable GeV gamma-ray sources.

Subject headings: gamma-rays: observations — pulsars:individual (Centaurus X-3)—acceleration of particles—binaries:eclipsing

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1. Introduction

Since its discovery, the Centaurus X-3 system has played a key role in the development of our understanding of galactic x-ray sources. For example, analysis of the UHURU satellite observations for this luminous x-ray source ($L_x \sim 10^{38}$erg s^{-1}) uncovered the first evidence for coherent x-ray pulsations from an object in a binary system (Giacconi, et al. 1971; Schreier et al. 1972). That discovery quickly led to a model wherein the pulsed Cen X-3 emission is generated by the accretion of matter from a companion star onto a rotating neutron star (Pringle and Rees 1972; Lamb et al. 1973) — a model that would subsequently become a standard model for galactic binary x-ray sources. More than two decades of multiwavelength observations and modeling have established that Cen X-3 is a disk-fed pulsar in orbit around an O-type supergiant companion (Nagase et al. 1992) and have provided important clues about the dynamic interaction of accretion disks and neutron star magnetospheres.

The Cen X-3 system also has the potential to play a key role in the development of our understanding of galactic gamma-ray sources and energetic particle acceleration. While controversial, reported detections of TeV gamma-ray emission from Cen X-3 (Caraminana et al. 1989; North et al. 1990) as well as TeV and/or PeV gamma-ray emission from eight other x-ray binary systems (reviewed by Weekes 1992, 1988), suggest that particle acceleration to very high energies occurs within the systems. One would expect these TeV/PeV gamma-ray emitters also to be substantial emitters of GeV gamma-rays. In this *Letter* we present measurements taken with the Energetic Gamma Ray Experiment Telescope (EGRET) aboard the Compton Gamma Ray Observatory (CGRO) that indicate the Cen X-3 system is, in fact, an intermittent source of GeV gamma-ray emission and that sporadic acceleration of particles to energies of at least a GeV must occur within the binary system.

2. An Outburst of Gamma Ray Emission from Cen X-3

The EGRET instrument is a gamma-ray telescope which provides imaging spectroscopy of gamma-ray sources at energies from 30 MeV to 30 GeV over a field of view that extends up to 40° from the pointing direction. During Cycle 4 of the CGRO observing program, EGRET was pointed toward the fourth quadrant of the galactic plane in the direction $l = 310.28°$ and $b = -4.99°$ for a one-week interval starting on 18 Oct 1994 (VP 402.0). Immediately afterward, the pointing direction was moved 3.7° to the direction $l = 306.73°$ and $b = -3.78°$ for the collection of an additional week of fourth quadrant galactic plane measurements (VP 402.5). Since the position of Cen X-3 was within 19° of the pointing direction during both the VP 402.0 and VP 402.5 observation intervals, we analyzed the accumulated data, to search for GeV gamma-ray emission from the Cen X-3 system as part of our survey of suspected TeV gamma-ray sources.

Our likelihood analysis for the VP 402.0 and VP 402.5 measurements of the Centaurus region revealed, using standard EGRET analysis techniques (e.g. Mattox et al. 1996), the presence of a significant source ($\sim 5.0\sigma$), with a test statistic peak located at $l = 292.20^{\circ}$ and $b = 0.48^{\circ}$, that was not detected during previous observations of the region (see §3). The 95% confidence position contour for the excess is given approximately by an ellipse centered on the peak position with a semi-major axis of $51.5'$, a semi-minor axis of $32.9'$, and a position angle of 41.0° measured eastward from north on the meridian of the major axis. Failure to detect the emission in earlier observations indicates that the excess is not an artifact associated with an error in the diffuse radiation model. Furthermore, both the size and shape of the test statistic confidence peak are consistent with the response expected for a point source, indicating that the excess is associated with a previously unknown EGRET source.

It is possible that the outburst of gamma-ray emission from the Centaurus region was generated by a background blazar which is unknown due to its low galactic latitude. However, all EGRET sources that display significant variability at high latitudes ($\mid b \mid > 10^{\circ}$) are associated with strong, flat spectrum, radio sources (von Montigny et al. 1995). In fact, Mattox et al. (1997) have shown that the peak gamma-ray flux of a blazar is correlated with its average 5 GHz radio flux. The gamma-ray flux associated with the November 1994 outburst, F(>100 MeV)= 9×10^{-7} cm^{-2}s^{-1}, would place a blazar in the top quartile for measured peak fluxes from blazars. Based on the median ratio of average 5 GHz radio flux to peak gamma-ray flux, $\sim 2 \times 10^{-10}$cm^{-2}s^{-1}mJy^{-1}, derived from the table of firm blazar associations given in Mattox et al. (1997), we estimate the gamma-ray blazar would be associated with a flat spectrum radio source with average 5 GHz flux of $\sim$ 4500 mJy. Our search of the SIMBAD database uncovered six PMN survey (Griffith & Wright 1993) radio sources which lie within the 95% position confidence contour. While radio spectral data is not available for the candidates, all of the sources have 5 GHz radio fluxes that are less than 70 mJy. Generation of the gamma-ray flux by a background blazar is therefore an unlikely possibility.

Centaurus X-3 is the most prominent galactic source that is consistent with the position of the EGRET source. The location of Cen X-3 ($l = 292.09^{\circ}$, $b = 0.34^{\circ}$) is only $10.7'$ from the likelihood peak and resides within the 50% position confidence contour. A search of the SIMBAD database for sources within the 95% position confidence contour uncovered many potential stellar and IR counterparts, but only one hard x-ray source in addition to Cen X-3 was found— the Einstein IPC Catalog source 2E 1119.6-6030. The unidentified 2E 1119.6-6030 source has an estimated Einstein broad-band (0.16-3.5 keV) flux of 2.5×10^{-13} ergs cm^{-2}s^{-1}. This flux is approximately 10^3 times weaker than Cen X-3 in the same energy band. The intensity of the Cen X-3 hard x-ray flux, absence of a plausible blazar counterpart, and previous reports of outbursts of TeV gamma-ray emission from that direction which are modulated at the Cen X-3 pulsar spin period, all lead us to identify the new EGRET source as Cen X-3.

3. Phase-Averaged Emission from Cen X-3

To derive the Cen X-3 photon spectrum from the VP 402.0 and VP 402.5 observations, exposure and count maps were accumulated for 7 EGRET energy ranges: 70-100 MeV, 100-150 MeV, 150-300 MeV, 300-500 MeV, 500-1000 MeV, 1-2 GeV, 2-4 GeV, and 4-10 GeV. The counts associated with Cen X-3 in each energy band were then derived by modeling the observed count maps with three components: an isotropic diffuse component, a Galactic diffuse component, and a point source at the known position of Cen X-3. Following the standard EGRET spectral fitting procedures, we found the best-fitting power-law for VP 402.0 and VP 402.5 is given by:

$$\frac{dN(E)}{dE} = 6.6(\pm 1.8) \times 10^{-10} \left(\frac{E}{328\ MeV}\right)^{-1.81 \pm 0.37} photons\ cm^{-2}\ s^{-1}\ MeV^{-1}. \tag{1}$$

The corresponding integral flux in the range 0.1-10 GeV is $9.2(\pm 2.3) \times 10^{-7}$ cm^{-2} sec^{-1}, which, for a Cen X-3 distance of 8 kpc (Krzeminski 1974; Hutchings et al. 1979, give 10±1 kpc), yields a phase-averaged gamma-ray luminosity of $L_\gamma(0.1 - 10 \text{ GeV}) \sim 5 \times 10^{36}$ erg s^{-1}.

We analyzed all EGRET observations of the Cen X-3 region with viewing angles <25° gathered through Cycle 5. Only one other viewing period, VP 014.0, showed evidence ($\sim 2.3\sigma$) for emission from Cen X-3 that exceeded the 95% confidence level. Comparison of the flux measured during VP402.0 and VP402.5 with the limit placed by joint analysis of all the data accumulated in the first three phases of the mission allows us to reject the constant gamma-ray flux hypothesis at the 99.96% confidence level. For VP 314.0 and VP 315.0 we derive a 95% confidence upper limit on the >100 MeV flux from Cen X-3 of 2.2×10^{-7} cm^{-2} s^{-1}. Comparison of that upper limit with our subsequent detection indicates variability on a ten month timescale at a confidence level of >99.9%.

4. Phase Analysis of the Gamma Ray Emission

We prepared the EGRET dataset to search for temporal modulation of the GeV gamma-ray emission because the x-ray emission from Cen X-3 displays modulation at two fundamental periods: a 4.8-second period associated with spin of the pulsar, and a 2.09-day period associated with orbital motion of the pulsar within the binary system (e.g. Nagase 1989). To optimize the signal-to-background ratio, we analyzed only the subsample of gamma-ray events with energies >50 MeV and positions within the 67% contour of the instrument Point Spread Function (Thompson et al. 1993) when centered on Cen X-3. The arrival times measured for gamma-rays generated by Cen X-3 are affected by motion of the detector relative to the binary system and, potentially, by motion of the source within the binary system. Correction for EGRET motion was achieved by transforming the observed event times, using the JPL DE 200 ephemeris and the known position of Cen X-3, to those that would be measured at our solar system barycenter (SSB). The contemporary Cen X-3 orbital parameters measured by CGRO/BATSE (Finger 1996), were used to correct for time delays generated within the binary system under the assumption that the gamma-ray emission is associated with the pulsar.

4.1. Spin Modulation

The x-ray pulsar in Cen X-3 can display rapid variations in spin frequency. Intermittent monitoring of the pulsar since its discovery by the UHURU team has established a gradual spin-up of the Cen X-3 pulsar, but this long term trend is often interrupted by alternating extended intervals of both rapid spin-up and spin-down (Nagase 1989; Finger et al. 1994). Indeed, contemporaneous CGRO/BATSE measurements of the x-ray pulse frequency show a strong drift during the interval that includes our EGRET detection (see Figure 1). This rapid variability of the pulse frequency compromises fixed frequency epoch folding or straightforward analysis with fast fourier transforms when searching the relatively long, two-week gamma-ray observation for spin modulation. Instead, we employed the technique, often applied when studying isolated gamma-ray pulsars, of epoch folding the data using an ephemeris derived from contemporaneous pulse measurements made at lower energies. To model the pulse frequency drift during the GeV gamma-ray outburst, we least-squares fit the functional form $\nu(t) = \nu_\circ + \dot{\nu}_\circ(t - t_\circ) + \frac{1}{2}\ddot{\nu}_\circ(t - t_\circ)^2$ to the BATSE pulse frequency measurements (Finger 1996) for the 37 day interval shown in Figure 1. The best fitting function parameters ($\chi^2 = 42.1$ for 10 degrees of freedom (DOF)) are given by: $\nu_\circ = 207.62829(\pm 0.00018)$ mHz, $\dot{\nu}_\circ = -3.004(\pm 0.385) \times 10^{-9}$ mHz s^{-1}, $\ddot{\nu}_\circ = -7.94(\pm 2.49) \times 10^{-16}$ mHz s^{-2}, and $t_\circ = 49643.0$ MJD=1994 October 18, 00:00 UT.

The large χ^2 indicates that the second-order polynomial fit to the BATSE measurements is not as good as one would like, the frequency residuals are of order 0.0006 mHz, but for model simplicity we have not fit higher order polynomials.

Our search for spin modulation of the gamma-ray emission began, after correcting the SSB photon arrival times for pulsar orbital motion, with epoch folding of the arrival times based on the modeled BATSE pulse drift ephemeris. To test for deviation from a statistically flat phase distribution, we employed the H-test statistic, which makes no assumptions about binning or the shape of the light curve (De Jager et al. 1989). Test statistics were calculated for modulation at frequency values within one independent frequency step for the accumulation (i.e., (14 days)$^{-1}$=0.00083 mHz) of the BATSE derived $\nu_\circ$ value, while the pulse frequency drift terms, $\dot{\nu_\circ}$ and $\ddot{\nu_\circ}$, were fixed at the BATSE derived values. The data for VP 402.0 and VP 402.5 data show a test statistic peak at $\nu = 207.62812(\pm 0.00014)$ mHz with an amplitude that indicates a chance probability of only 0.47% that the event arrival times are consistent with a flat phasogram. If, as observed at x-ray energies (Nagase 1989), the gamma-ray modulation has a broad pulse structure, then the generalized Rayleigh test with two harmonics, Z_2^2, would provide a more sensitive test for modulation (Buccheri et al. 1983). Indeed, when we apply the Z_2^2 test to the data, we again find a peak at a frequency which is consistent with the x-ray pulse frequency and an amplitude that corresponds to a chance probability for consistency with a flat phase distribution of 0.16%. Since the modulation search was limited to a range about the BATSE value which is the independent frequency step size for the accumulation, the detection significance was not devalued for independent frequency trials. We did, however, search a broader frequency range, 207.625-207.630 mHz, for other peaks and found none with comparable amplitude (Figure 2). The statistical tests therefore indicate gamma-ray modulation at the Cen X-3 pulsar spin frequency with a significance level comparable to a 3σ detection.

We performed a number of tests with control datasets to examine the plausibility of associating the observed modulation with the Cen X-3 pulsar. First, identical timing analyses were performed on VP 402.0 and VP 402.5 data collected at four additional positions within the EGRET field of view. Those control positions, all located more than 15° from Cen X-3, included three positions with viewing angles comparable to Cen X-3 ($\sim$15°), and one with a viewing angle of 5°. None of the control data sets showed a probability peak anywhere in a search range from 207.625 mHz to 207.630 mHz as large as the Cen X-3 peak, and no significant peaks indicating modulation in the expected BATSE pulsation frequency range were found. Second, since the pulsar timing analysis employs a binary ephemeris, we re-analyzed the data for the Cen X-3 position without including the binary orbit timing corrections. The peak within the expected BATSE frequency range disappeared when the binary correction was removed. The control results are therefore consistent with expectations for association of the observed modulation with the Cen X-3 pulsar.

4.2. Orbital Modulation

Our search for 2.09-day orbital modulation of the gamma-ray emission began with an epoch folding of the SSB arrival times employing the contemporary x-ray orbital ephemeris measured by CGRO/BATSE (Finger, 1996). If the gamma-ray emission is generated by the pulsar, one would expect periodic occultation of the emission by the optical companion. After renormalizing the counts in each phase bin to correct for exposure time, we found 68.0 events (source+background) of a total 264.4 events occurred during the interval of x-ray occultation ($|\ \phi\ |<0.12$)—consistent with a steady emission hypothesis. We also constructed phasograms to test for deviations from orbital phase uniformity. Our χ^2 test for uniformity of a 20-bin phasogram yielded $\chi^2 = 17.3$ for 19 DOF. A fit to a 50-bin phasogram for the same events yielded $\chi^2 = 52.1$ for 49 DOF, although one bin ($\phi = 0.04 - 0.06$) showed a large deviation: 13.3 events versus an expected 5.3 events after exposure correction. The results from our statistical tests therefore do not allow one to reject the null hypothesis that the EGRET gamma-ray emission is unmodulated at the orbital period.

5. Discussion

The positional coincidence of our new EGRET point source with Cen X-3 and the evidence we found for gamma-ray modulation at the known pulsar spin period constitute compelling arguments for associating the outburst of >100 MeV gamma-ray emission with the Cen X-3 system. Contemporaneous BATSE monitoring of the x-ray pulse frequency indicate that the Cen X-3 pulsar was undergoing an interval of rapid spin-down, $\dot{\nu} \sim -3$ pHz/sec, during the GeV gamma-ray outburst. Furthermore, the failure of BATSE to detect pulsed x-ray emission during several 2-day intervals (Figure 1) indicates the pulsed flux decreased during portions of the EGRET detection interval. Unfortunately, simultaneous measurements of total x-ray flux are not available, so it is not clear whether the total flux or just the pulsed fraction varied. Long-term pulse frequency monitoring by BATSE show 20-day averaged frequency derivatives, $\dot{\nu}$, that range from -6 pHz/sec to + 10 pHz/sec (Finger et al. 1992). Since such frequency drifts can correspond to as many as 10 independent frequency steps for a Fourier periodicity analysis of a nominal two-week EGRET observation of Cen X-3, it is clear that contemporaneous x-ray measurements of the pulsar spin frequency are essential when searching the sparse gamma-ray data for spin modulation.

Our EGRET observations of Cen X-3 arguably represent the first evidence for variable GeV gamma-ray emission from an x-ray binary system. Taking pre-CGRO observations of the Cygnus X-3 system at face value—a reported detection of >50 MeV gamma-rays with the SAS-2 satellite (Lamb et al. 1977) and a subsequent non-detection by the COS B satellite (Bennett et al. 1977)—indicates variability in the >100 MeV gamma-ray emission for that x-ray binary system. This variability hypothesis was attractive for Cyg X-3 because the SAS-2 detection occurred only a few months after a giant radio outburst (Gregory et al. 1972). However, measurements of Cyg X-3 with EGRET, while including periods just before and after a giant radio outburst, show a *steady* GeV flux that is about a factor of 5 below the reported SAS-2 flux (Michelson et al. 1992; Mori et al. 1997). On the other hand, the EGRET measurements of Cen X-3 we have presented in this paper yield a 0.1-10 GeV gamma-ray flux of 9.2×10^{-7} cm^{-2}s^{-1} in October of 1994 and a 95% confidence upper limit of $< 2.2 \times 10^{-7}$ cm^{-2}s^{-1} for January of the same year. Those measurements, taken with a single instrument, indicate that the GeV gamma-ray flux from Cen X-3 can vary significantly on a timescale of ten months.

The detection of GeV gamma-rays from Cen X-3 is consistent with the reports of outbursts of TeV gamma-ray emission by observers using ground-based atmospheric Cerenkov telescopes. The Durham Group has reported detections of a variable >250 GeV gamma-ray flux that is modulated at the pulsar spin period (Caraminana et al. 1989). They derive a peak flux for >250 GeV gamma-rays of $\sim 3 \times 10^{-10}$cm^{-2}s^{-1}, which is comparable to the >250 GeV flux, 1.3×10^{-10}cm^{-2}s^{-1}, predicted by straightforward extrapolation of the best fitting spectral parameters derived for the EGRET outburst. The Potchefstroom group has independently reported evidence for spin modulated gamma-ray emission from Cen X-3 at energies >1.9 TeV (North et al. 1990). Both groups found the modulated emission was restricted to orbital phases ϕ ∼0.7-0.8. However, at GeV energies we found the emission has a much broader orbital phase distribution and, with the available data, cannot rule out the presence of GeV emission throughout the 2.09 day orbital period.

Production of the EGRET detected gamma-rays requires, at least, sporadic acceleration of particles to GeV energies within the binary system. The phase-averaged GeV gamma-ray luminosity of 5×10^{36} erg s^{-1} is comparable to that measured during the TeV outbursts, but is 1.5 orders of magnitude less than the soft x-ray luminosity measured during x-ray high states and a factor of 3 smaller than the high state hard x-ray luminosity. Therefore, depending on the details of the gamma-ray production mechanism, less than ∼10% of the total power generated during accretion needs to be directed into energetic particle acceleration by Centaurus X-3.

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Fig. 1.— The Cen X-3 pulse frequency history measured by BATSE in the 20-50 keV energy range for a 37-day interval that brackets the EGRET detection. The Truncated Julian Day (TJD) is related to the Modified Julian Day (MJD) and the Julian Day (JD) by TJD=MJD-40,000.0=JD-2,440,000.5 so that, for example, 9643.0 TJD=18 Oct 1994 at 00:00 UT.

Fig. 2.— H-test statistical estimate of probability that the gamma ray emission is modulated at frequencies in the vicinity of the x-ray pulse frequency. The range plotted for the BATSE frequency denotes the formal error derived from our least squares fit to the pulse frequency history.

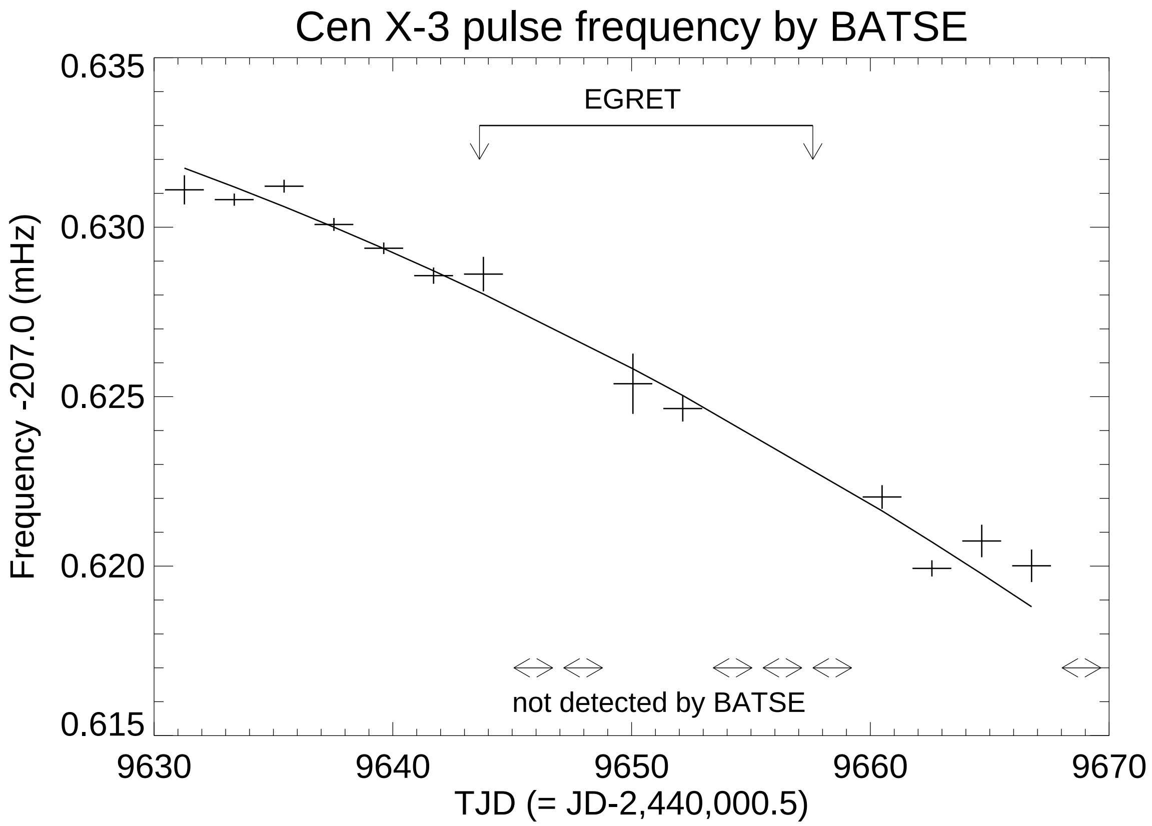
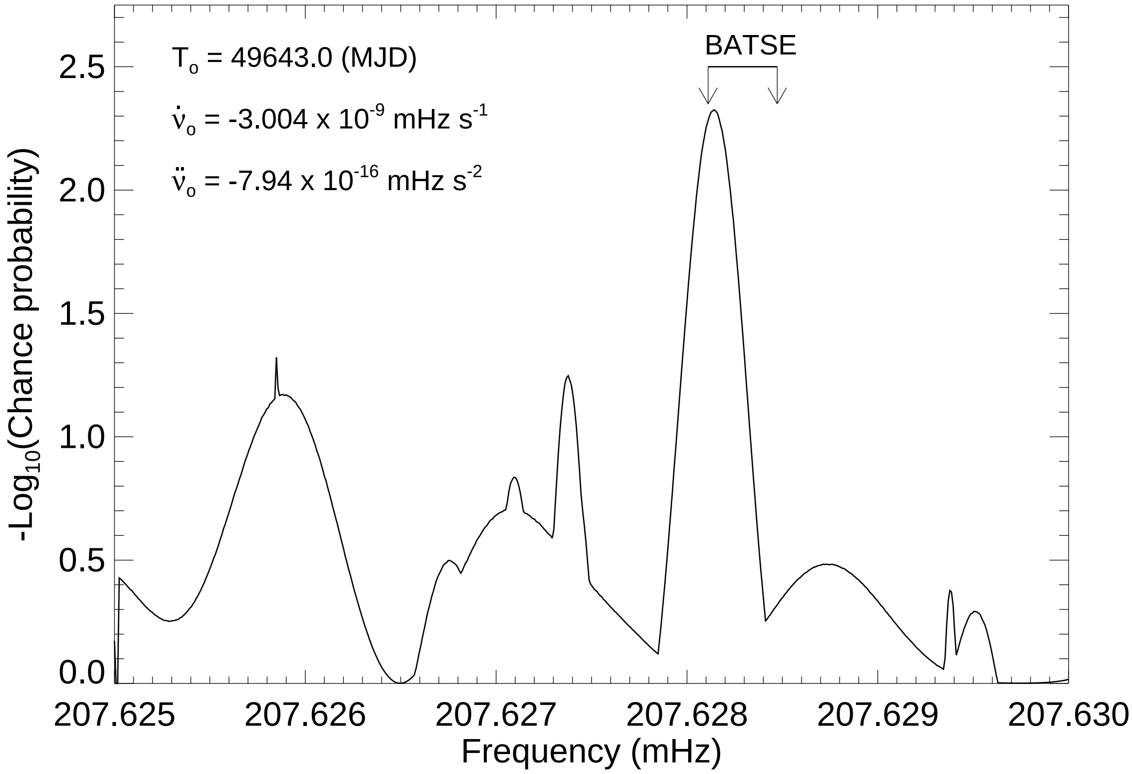


Fig. 1



T_o = 49643.0 (MJD)
$\dot{\nu}_o$ = -3.004 x 10^{-9} mHz s^{-1}
$\ddot{\nu}_o$ = -7.94 x 10^{-16} mHz s^{-2}
BATSE
-Log_{10}(Chance probability)
0.0
0.5
1.0
1.5
2.0
2.5
207.625
207.626
207.627
207.628
207.629
207.630
Frequency (mHz)

Fig. 2