PROCEEDINGS OF SCIENCE

X-ray binaries: a key corollary science with Crystal Eye

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X-ray binaries (XRBs) are strong hard X-ray emitters and among the most common sources in the Galactic plane within the 20–100 keV energy range. A handful of XRBs, both transient and persistent, have also been detected as gamma-ray emitters by Fermi/LAT and AGILE-GRID above 30 MeV (e.g., Cyg X-3, Cyg X-1, and V404 Cyg), yet the origin of this gamma-ray emission remains largely unknown. Moreover, the energy band between approximately 500 keV and 30 MeV has remained substantially unexplored due to the limited sensitivity of current X-ray and gamma-ray telescopes. Crystal Eye will continuously monitor the sky in search of Gamma Ray Bursts from about 10 keV to 30 MeV. It will also be capable of detecting bright hard X-ray transients, such as XRBs hosting black holes as compact objects. Here, we explore how Crystal Eye can contribute to the study of XRBs by monitoring transient events and tracking their evolution over time. Additionally, we investigate how it could enable continuous monitoring of persistent XRBs and extend the detectable energy range of these sources to 500 keV–30 MeV.

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1. Crystal Eye detection strategy and scientific goal

Crystal Eye (CE) is a compact gamma-ray detector designed to explore the electromagnetic spectrum in the energy range of about 10 keV to 30 MeV [1] [2]. This all sky monitor will detect transient explosive and fast episodes of the Universe. The primary target of CE is the study of transient phenomena, including Gamma-ray Burst prompt emission, magnetar flares and Solar flares. In the new multi messenger era the CE detector will be necessary to link transient phenomena like, for example, Gamma ray burst to gravitational wave (GW) events from binary neutron stars (BNS), as the case of the detected GRB 170817A and GW contemporaneous events in 2017. CE is designed to autonomously transmit burst alerts with low latency, enabling rapid dissemination of transient coordinates via the Gamma-ray Coordinates Network (GCN) through high-priority data links such as EDRS or VHF. This real-time capability ensures that follow-up observatories across the electromagnetic and gravitational wave spectrum can respond promptly to high-energy transients detected by CE. CE, indeed, operates with an 8-second sliding observational window, during which data are continuously acquired and averaged. A real-time convolutional neural network (CNN) analyzes this moving average to detect "hotspots"—sudden increases in photon flux on timescales 8s. When such a transient is found, the onboard system can autonomously localize the event and generate an alert, enabling rapid follow-up by other observatories. This makes CE well-suited for promptly detecting short and energetic transients such as flares from microquasars, magnetars, or GRBs. While optimized for gamma-ray bursts (GRBs), CE will also be able to monitor and detect hard X-ray transients, including outbursts and flares from X-ray Binaries (XRBs). For slower transients evolving over hours or days, the rise in flux does not fall within the CNN's time window, making real-time localization unfeasible. However, even when the source cannot be localized directly by CE, its flux and spectral evolution can still be monitored—provided its sky position is known from external alerts or catalogs. In this case, CE continuously records background data along each orbit and, knowing the expected source direction, can isolate the subset of detector elements that should contain the signal. This enables the extraction of temporal and spectral features over longer timescales. A dedicated convolutional neural network (CNN) may be employed to analyze the background evolution and reveal subtle source signatures. In parallel, a more traditional and robust approach is offered by the Earth Occultation Technique (EOT), which can be naturally exploited by CE's zenith-pointing design to detect flux steps as the source rises or sets behind the Earth limb, with reduced need for post-processing.

2. X-ray Binaries in the CE domain

CE's wide energy band (10 keV–30 MeV) enables valuable ancillary science beyond its primary GRB focus. Among the key targets are variable and persistent sources such as X-ray Binaries (XRBs), AGN, the Galactic Centre, and Soft Gamma Repeaters (SGRs).

XRBs are among the brightest hard X-ray emitters in the Galaxy, particularly in the 20–100 keV range, and often show variability from milliseconds to days. Several, including Cygnus X-1, Cygnus X-3, and V404 Cygni, have been detected above 30 MeV by Fermi/LAT and AGILE, suggesting relativistic particle acceleration. The mechanisms behind these emissions remain uncertain. Proposed models include inverse Compton scattering in coronae or jets, synchrotron self-Compton processes in compact outflows, hadronic interactions producing pions, and hybrid Comptonization involving both thermal and non-thermal electrons.

Discriminating among these scenarios requires coverage of the intermediate 0.5–30 MeV band, which remains poorly explored due to instrumental limitations. CE, with its 10 keV–30 MeV range and all-sky monitoring, can fill this gap between soft X-ray (e.g., MAXI, NICER) and high-energy gamma-ray (e.g., Fermi/LAT) observatories. CE will help: (1) Constrain spectral cutoffs and breaks, which indicate characteristic electron energies and cooling processes; (2) Detect transient high-energy tails during state changes or flaring activity, potentially associated with jet formation; (3) Monitor spectral evolution during outbursts in real time, revealing accretion-high energy emission connections. By delivering simultaneous broad-band spectra, CE can reduce model degeneracies and enhance our understanding of accretion, jet formation, and particle acceleration in strong-gravity environments.

2.1 Variability of the XRBs

The temporal behavior of X-ray binaries (XRBs) in the X-ray and hard X-ray domains is characterized by two main types of variability: long outburst events and short flare episodes. The former are typically associated with spectral state transitions in the accretion flow around the compact object. They manifest as gradual and sustained increases in flux, lasting from several days to weeks, and are observed across a broad energy range—from soft X-rays up to hard X-rays ($\sim$ 1–200 keV). These events have been extensively studied by instruments such as INTEGRAL, AGILE, BeppoSAX, RossiXTE, and NuSTAR, and are often accompanied by changes in the source's timing properties and jet activity. In systems hosting a neutron star (NS), an additional class of variability is observed in the form of Type I X-ray bursts, which result from thermonuclear ignition of accumulated matter on the NS surface. These bursts are characterized by a rapid rise ($\sim$ 1 s) followed by an exponential decay ($\sim$ 10–100 s) and peak in the 1–40 keV energy range. Although intrinsically soft, their high luminosity may allow them to be detected by CE in its lower energy range, as demonstrated by similar events observed by GECAM from sources like 4U 0614+091 [3]. Flare events, instead, are shorter in duration (seconds to minutes) and often less predictable. They can originate from instabilities in the accretion disk, magnetic reconnection events, or sudden changes in jet activity. Some flares are observed to extend into the hard X-ray and gamma-ray domains, indicating the presence of non-thermal processes and particle acceleration. Such episodes have been observed in systems like Cyg X-3 and V404 Cyg, which have shown emission above 100 keV, and in some cases, up to GeV energies as detected by AGILE-GRID and Fermi/LAT. CE's wide energy coverage and continuous monitoring capability make it well-suited to capture both types of variability, providing time-resolved spectra that can help disentangle the underlying physical mechanisms.

3. Monitoring the XRBs with CE

CE will be capable of detecting very fast changes in flux from XRBs. Combined data will be used to study state transitions, jet activity, and flare events. As discussed in section 1, in the standard mode of observation CE can provide light curves with time bin of 8 seconds. With this time bin the sensitivity curve of CE could reveal the most energetic flare. For example of the 2015 flare of

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V404 Cygni that was observed with INTEGRAL, AGILE and FERMI, could be clearly detected with the CE sensitivity curve for 2/8 sec of integration time. For other sources, or less energetic events, that need more integration time to be observed it possible to use a different method to collect observations and increase the integration time: the Earth Occultation technique (EOT).

3.1 Earth Occultation Technique

The EOT exploits the periodic occultation of celestial sources by Earth as seen from the satellite. Each occultation produces a step-like feature in the detector count rate, which can be modeled to estimate the source flux even in the absence of direct imaging. CE leverages Earth occultation to extract source fluxes and monitor long-term emission. This technique is especially useful for persistent sources that are not bright enough to trigger direct detection.

3.1.1 Model for Earth Occultation Fitting

The observed count rate $r(t, E_{\text{ch}})$ in energy channel E_{ch} and time t is modeled as:

$$r(t, E_{\text{ch}}) = b_0 + b_1(t - t_0) + b_2(t - t_0)^2 + \sum_i a_i(E_{\text{ch}}) S_i(t, E_{\text{ch}}) \tag{1}$$

where b_0, b_1, b_2 represent the background, and a_i scales the model signal S_i, which incorporates the detector response R, atmospheric transparency T, and the source spectrum $f(E_\gamma)$ [5].

Figure 1 show, as example, the well agreement from the EOT data from GBM (12–50 keV) and the Swift/BAT public transient monitor data (15–50 keV) [5].

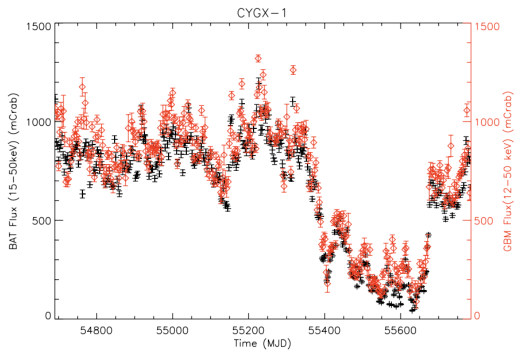

Figure 1: Comparison between the 12–50 keV GBM EOT results data of Cyg X–1 for the three-year interval (2008-2011) along with the same time interval for Swift/BAT. The results are compatible. From [5].

3.1.2 Sensitivity Scaling with Occultation Steps

To improve sensitivity, multiple occultation steps can be combined. Assuming statistically independent measurements, the sensitivity improves as:

$$S_N = \frac{S_1}{\sqrt{N}} \tag{2}$$

where S_1 is the sensitivity for a single step, and N is the number of occultation events. This strategy is critical for faint or transient sources, where the signal from a single event is often below the background. Each Earth occultation step has an effective duration of several seconds, depending on the geometry and satellite altitude.

4. Detection Time Estimate for V404 Cygni

V404 Cygni is a transient black hole XRB known for its powerful and broadband outbursts.

To evaluate the detection capabilities of CE in the hard X-ray and MeV domain, we consider the broadband SED of V404 Cyg during its 2015 outburst. During this outburst the source exhibited a hard spectrum reaching up the MeV regime. Fermi-LAT measured an integrated flux between 50–400 MeV of approximately $F_{\gamma,\,50-400\,\mathrm{MeV}} \simeq 4.1 \times 10^{-10}$ erg cm^{-2} s^{-1}, which provides constraints on the spectral shape and normalization at high energies. We assess two observational modes for CE: direct detection and EOT.

4.1 Direct Detection

At the energy of 100 keV, the minimum detectable flux (MDF) for CE for 8-second integration is estimated to be:

$$F_{\mathrm{MDF,\,8s}\ (100\,\mathrm{keV})} \simeq 2 \times 10^{-3}\ \text{photons cm}^{-2}\ \text{s}^{-1}\ \text{keV}^{-1}.$$

From the fitted spectral model [6] the flux of the source V404 Cygni at 100 keV is:

$$F_{\mathrm{V404}\ (100\,\mathrm{keV})} \simeq 0.1\ \text{photons cm}^{-2}\ \text{s}^{-1}\ \text{keV}^{-1} \gg F_{\mathrm{MDF,\,8s}\ (100\,\mathrm{keV})},$$

exceeding the CE threshold by a factor of about 50.

Integration over the 50–500 keV band yields a total flux:

$$F_{\mathrm{V404}\ (50-500\,\mathrm{keV})} \approx 0.02\ \text{photons cm}^{-2}\ \text{s}^{-1},$$

which is sufficient for direct detection in less than 10 seconds. This confirms that CE can detect an outburst from V404 Cyg in a single exposure as short as 8 seconds.

This result is clearly visible from Figure 2.

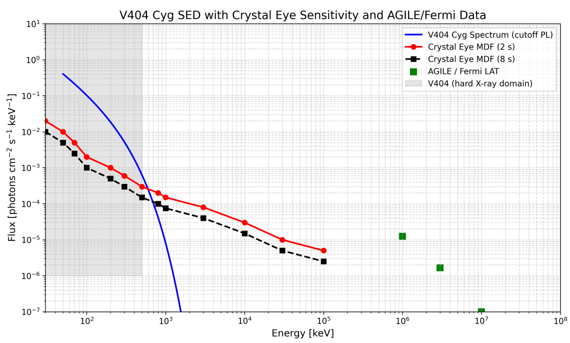

Figure 2: Broadband SED of V404 Cyg during the 2015 outburst, including hard X-ray data (50–500 keV) and Fermi-LAT detection in the 50–400 MeV range. Overlaid is the estimated *Crystal Eye* sensitivity for direct exposure (2 s and 8 s).

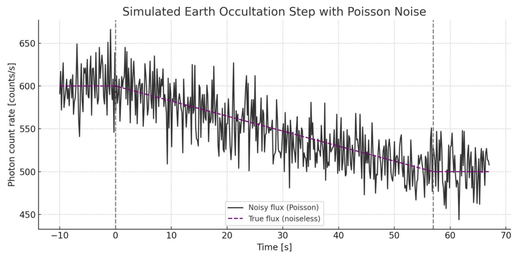

Figure 3: Earth Occultation step simulated for V404 Cygni with CE.

4.2 Detection via Earth Occultation Technique

In the occultation method, CE monitors step-like changes in count rate as sources rise or set behind the Earth. We simulated a EOT for V404 Cyg based on the CE orbit duration (90 minutes), geometry and inclination (5° of inclination and 550 km of altitude), obtaining an effective duration of the step of about 60 seconds as showed in Figure 3.

For robust detection across the full hard X-ray SED, especially above 500 keV, where both the source flux and detector sensitivity decrease, a larger number of occultation steps is advisable. Using the source fluxes $F_{\mathrm{V404}}(E)$ from the observed cutoff power-law model, we compute the number of occultation steps required from eq. 2 as:

$$N = \left(\frac{F_{\mathrm{MDF}}(E)}{F_{\mathrm{V404}}(E)}\right)^2 .$$

We use the energy-dependent 2-seconds MDF values derived from instrument simulations, with values ranging from 2×10^{-2} at 30 keV to 5×10^{-6} at 100 MeV.

Taking into account the coordinate of the source and satellite attitude we estimate 10 occultations per day, so for V404 Cygni the total integration time in one day is 600 s. So we thus estimate the total time, in unit of day, needed to compute N steps necessary for the detection:

$$T_{\mathrm{d}} = \frac{N \times 2\ \mathrm{s}}{600\ \mathrm{s/d}}.$$

A summary of detection time estimates at different energies is presented in Table 1.

Table 1: Detectability of V404 Cyg in outburst using the Earth Occultation Technique (EOT) with CE. Flux values $F(E)$ are taken from the cutoff-powerlaw model. The MDF corresponds to CE estimated sensitivity at 2-second exposure.

Energy (keV)	**Flux $F(E)$** (photons cm^{-2} s^{-1} keV^{-1})	**MDF (2s)** (photons cm^{-2} s^{-1} keV^{-1})	N **steps**	**Time** (days)
500	4.8×10^{-4}	3.0×10^{-4}	0.4	<0.1
1000	1.5×10^{-5}	1.5×10^{-4}	100	1/3
2000	1.0×10^{-7}	9.5×10^{-5}	9×10^5	1500
3000	1.4×10^{-9}	8.0×10^{-5}	3×10^9	5442176

If an integration time of 8 seconds is assumed for each occultation step instead of 2 seconds, the sensitivity improves by a factor of $\sqrt{4} = 2$, reducing the minimum detectable flux accordingly.

In conclusion as a summary of the detection time from the different method is reported in Table 2.

Table 2: Estimated detection times for V404 Cyg during outburst with *Crystal Eye*.

Observation Mode	Detection Time	Notes
Direct (8 s exposure)	$\lesssim$10 s (one single exposure)	source flux exceeds MDF at 100 keV
Earth Occultation (EOT)	<1 day (<1000 keV), <1500 days (<2000 keV)	Based on 10 occultations of 60 s/day

5. Monitoring Capabilities of CE for X-ray Binaries

In addition to GRBs, CE is well suited to monitor known XRBs, particularly in the hard X-ray domain ($\gtrsim$30 keV). While some sources are persistently bright (e.g., Cyg X-1), others show recurrent outbursts (e.g., GX 339–4, Aql X–1) or rare, intense flaring events (e.g., V404 Cyg, Cyg X-3). We can extimate how CE can detect such sources either via direct pointed observations or by leveraging the EOT across the sky.

Based on the instrument's MDF in the 40–100 keV range (6.4×10^{-3} photons cm^{-2} s^{-1} keV^{-1} in 2 seconds), and assuming typical source averaged fluxes in the same energy band as reported in [8] we estimate the expected detection times and occultaions number summarized in Table 3.

Source	Flux 40–100 keV erg cm^{-2} s^{-1}	Direct Det. ks	EOT Det. day	Notes
Cyg X-1	8.3×10^{-9}	~0.04	2	Pers., var.
Cyg X-3	6.7×10^{-10}	~6.2	310	Highly var.
GX 339–4	4.1×10^{-10}	~16.8	840	Trans.

Table 3: Estimated detection times for selected X-ray binaries using CE, based on source averaged flux and instrument sensitivity in the 40–100 keV band (MDF for 2 seconds). The EOT detection time is estimated considering 10 occultation of 2 s per day.

6. Discussion of Earth Occultation Assumptions

The estimated detection obtained are depending on flux level, integration strategy, and background model efficiency. Our estimates for detection times using the EOT rely on the following assumptions:

- number of occultations: EO observations are limited by the number and duration of occultation events per day.
- MDF: we assumed each occultation providing an effective integration equivalent to 2 s (matched to CE's MDF reference),
- Effective area: assumed comparable to direct exposure, corrected by geometry and detector response near limb angles.

- Background modeling: a quadratic fit is assumed locally, consistent with historical EOT analyses.
- Integration gain: sensitivity is scaled as $1/\sqrt{N}$ assuming independent steps.

7. Conclusions

Ancillary science from CE will complement major past and present observatory results like NuSTAR, Swift, INTEGRAL, Agile, Fermi-GBM, SVOM, and GECAM. Collaboration and coordinated observations will enhance the science return from CE.

According to our simulations, CE can detect powerful flares, like that of V404 Cyg, within a few seconds through direct observations. The EOT remains essential for: regular monitoring of persistent but variable sources; complementing limited sky coverage in direct mode; and extending detection capability to multiple energy bands simultaneously. Our integration time estimates (ranging from 1 to 20 days for flare events, and up to 2-3 years for monitoring faint but steady XRB sources) are consistent with results from other satellites that have employed this technique (e.g., BATSE), suggesting that these estimates are realistic given CE's design sensitivity. However, full modeling of CE's orbit, attitude constraints, and Earth horizon geometry is required for precise forecasting. It is important to note that the effectiveness of EOT depends on the number of occultation events and on accurate background estimation, both from ground simulations and in-flight data.

Our preliminary study confirm that CE, through both direct and occultation modes, is well-positioned to fill the MeV observational gap for X-ray binaries and transient monitoring. With regular occultation events and effective background modeling, CE can track flux variability and detect transients with improved energy limit and unpredicted temporal resolution. Such observations in the poorly explored 0.5–10 MeV range will help constrain particle acceleration, improve understanding the high-energy spectral transitions emission mechanisms near the compact object, and complement existing monitoring by Fermi, Swifts, and future MeV missions.

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