OVERVIEW OF THE CYCLONE HARD X-RAY OBSERVATORY

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ABSTRACT

In response to the recent NASA-SMEX Announcement of Opportunity, our collaboration proposed the *Cyclone* Hard X-Ray Observatory. *Cyclone* is a broadband pointed astrophysical observatory, combining the highest spectral resolutions ($E/\Delta E \sim$30-300) and angular resolutions (15") achieved in the optimized hard X-ray range (10-200 keV). The instrument consists of 19 co-aligned rotation modulation collimator (RMC) telescopes, each with a high spectral resolution, 6-cm diameter germanium detector (GeD) covering energies from 3 keV to 600 keV. Both the optics and detectors are actively shielded with 15-mm BGO to gain low background and high sensitivity to astrophysical sources. A 550-km altitude, circular equatorial orbit also minimizes background. Building strongly upon instrumental heritage from the High-Energy Solar Spectroscopic Imager (HESSI) program, *Cyclone* would be ready for launch by September 2003. All of the data and software will be made public immediately, and the observatory will maintain a large Guest Observer Program. This paper provides a brief overview of the scientific goals, instrument design, and expected performance. A more detailed instrument paper has been presented elsewhere (Boggs et al., 2000).

Key words: high energy astrophysics; x-ray/gamma-ray detectors; satellite missions.

1. INTRODUCTION

High-resolution observations of astrophysical nuclear line emission is the highest priority scientific goal for future hard X-ray/soft γ-ray missions (NASA/GRAPWG Report , 1999). Almost all of the important isotopic decay chains produced in supernova nucleosynthesis (Diehl & Timmes , 1998) result in nuclear line emission in the hard X-ray range (10-200 keV) as well as the soft γ-ray range (0.3-10 MeV), e.g., ^{44}Ti, ^{56}Ni, ^{57}Ni, ^{26}Al-^{60}Fe. *Cyclone* is optimized to build off the successes of the upcoming INTEGRAL mission, performing narrow FOV ($\sim 1°$), targeted observations in the 10-200 keV energy band, and achieving unprecedented hard X-ray spectral resolutions ($E/\Delta E \sim 30-300$), angular resolutions (15"), and nuclear line sensitivities (Table 1). *Cyclone* is an order of magnitude more sensitive than Integral/SPI to nuclear line emission at hard X-ray energies, with factors of $\sim$3 better spectral resolution. The improvements in hard X-ray performance over Integral/SPI result from (i) the use of GeDs optimized for energies below 200 keV, and (ii) *Cyclone*'s decreased background due to a much narrower FOV and equatorial orbit. For imaging, *Cyclone* gains 50 times better angular resolution than the imager Integral/IBIS, and 500 times better than Integral/SPI. *Cyclone* will map the sites of 68/78 keV ^{44}Ti nuclear line emission in young supernova remnants (SNRs), which have typical diameters <10' (Cas A 4', Kepler 3.4', Tycho 8').

Cyclone is also a powerful observatory for the study of compact objects. *Cyclone*'s spectral resolution will resolve the electron cyclotron lines in magnetized neutron stars, and potentially discover proton cyclotron lines in magnetars. Timing of every photon to 1μs will help explore the detailed accretion structure and magnetic field geometry in these objects. The broadband coverage (3-600 keV) is ideal for studying the multi-component spectra of black holes. Sub-arcminute imaging of nonthermal emission in Galactic supernova remnants and extragalactic jets will pinpoint and characterize enigmatic sites of particle acceleration. Spatially resolved spectroscopy of crowded Galactic fields will detect and

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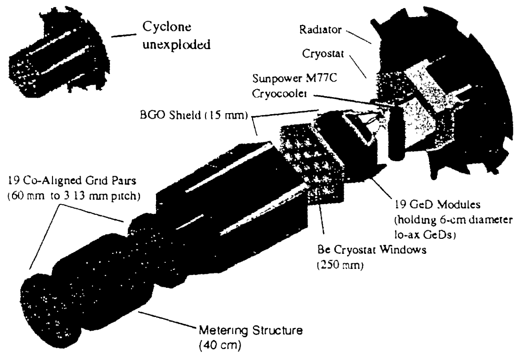

Figure 1. Exploded view of the Cyclone *scientific instrument showing the major components. The unexploded view is shown in the upper left corner (courtesy P. Turin, SSL/UCB).*

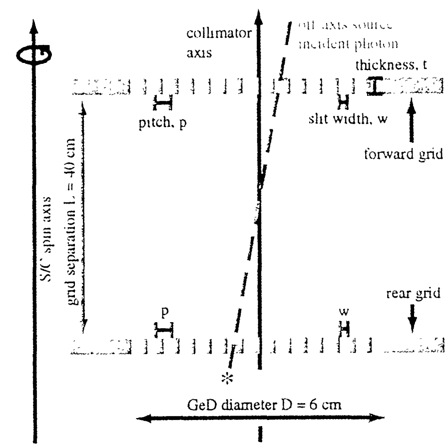

Figure 2. Sketch of the instrument parameters that define Cyclone*'s imaging capabilities.*

classify new sources, including the massive black hole at the center of our Galaxy. A systematic survey of infrared-identified candidates will reveal obscured active galactic nuclei, quantifying their contribution to the 30 keV peak in the cosmic X-ray background.

Launch in 2003 would maximize *Cyclone*'s scientific impact. Integral (2002) will have been observing for over a year, providing many new sources for detailed study. Swift (2003) and MAXI (2003) will provide powerful all-sky monitoring capabilities. Chandra and XMM will be fully active, and *Cyclone* will provide a unique hard X-ray complement with its broad energy band (extending down to ~3 keV) and high angular resolution. During its 2-3 year mission *Cyclone* will perform 100-200 detailed source observations. For a 3-year mission, *Cyclone* will perform coordinated observations with GLAST (2005). Rapid, direct access by the astrophysics community to the *Cyclone* data and software, combined with a large Guest Observer Program (50% during its first three years, 100% for an extended mission) ensures the optimal scientific return from the mission.

2. TELESCOPE DESIGN

Cyclone utilizes an array of 19 co-aligned Rotation Modulation Collimator (RMC) telescopes (Figure 1), each consisting of a pair of widely separated 1-D opaque grids mounted in front of a hard X-ray GeD. As the spacecraft rotates, the RMCs convert the spatial information from the FOV into temporal modulation of the photon counting rates of the GeDs. A bismuth germanate (BGO) scintillator shield encloses the bottom and sides of the GeDs and RMC grids to minimize background. The energy (70 eV/channel) and arrival time ($1\mu s$) of every photon together with aspect data are recorded onboard and automatically telemetered within 24 hours. With these data, the hard X-ray images and spectra can be reconstructed on the ground. *Cyclone* builds upon strong instrumental heritage from HESSI (Lin et al., 1998; Dennis et al., 1996) and commercially available components, allowing the observatory to be launched by September 2003. A more detailed description of the instrument design and performance has been presented in Boggs et al. (2000).

2.1. Imaging Array

Each grid in an RMC (Figure 2) is a planar array of equally spaced hard X-ray-opaque slats separated by transparent slits. The slits of each pair of grids are parallel to each other and their pitches (p) are identical. For complex sources, and over small rotation angles, the convolution of the sky brightness with the grid transmission, as measured by the count rate in the detector, provides a direct measurement of a single Fourier component of the sky brightness angular distribution (e.g., Prince et al. (1988)). The 19 RMCs measure amplitudes and phases of over 10^3 Fourier components in a half rotation, ensuring that the image quality is limited by statistics, and not by the finite number of measured Fourier components. Observations from many rotations can be combined, whether or not there is good statistics in any single rotation or Fourier component. Spectra can be obtained for each feature in the image, providing true high-resolution imaging spectroscopy.

For *Cyclone*, the separation between grids is $L = 40\ cm$ and the grid pitches range from 60 μm to 3.13 mm in steps of $3^{1/5}$, resulting in angular resolutions (defined as p/(2L)) that are spaced logarithmically from 15" to 13.5'. Molybdenum was selected as the grid material for its stopping power, activation properties, and ease of fabrication. The grids range in thickness from 8.0 mm for the coarsest grids to 1.9 mm for the finest. The technique developed by Thermo Electron Tecomet for HESSI will be used to fabricate all 38 grids. The grid properties and alignment will be calibrated to ~ 1% using the NASA/GSFC optical and X-ray characterization

Table 1. Cyclone *Mission Characteristics*

Energy Range	10-200 keV Optimized, 3-600 keV Full
Energy Resolution	350 eV < 20 keV, 550 eV @ 78 keV (FWHM)
Angular Resolution/Range	15"-13.5' (FWHM)
FOV	$\sim 1°$
Total Detector Area	540 cm^2 GeDs
Effective Photopeak Area	105 cm^2 @ 78 keV
Continuum Background	$\sim 1.0 \times 10^{-4} ph/cm^2/s/keV$ (40-200 keV)
Narrow Line Sensitivity	$4 \times 10^{-6} ph/cm^2/s$ @ 78 keV, $(5\sigma, 10^6 s)$
Point Source Sensitivity	0.12 mCrab (10-100 keV), $(5\sigma, 10^6 s)$
Orbit	Equatorial LEO (550 km)
Spacecraft	Spin Stabilized, 60-s Rotation Period
Pointing Requirements	$\leq 0.5°$
Aspect Performance	2" Pitch & Yaw, 20" Rotation
Launch Date	September 2003
Mission Lifetime	2 years Nominal, $\geq$3 years Desired

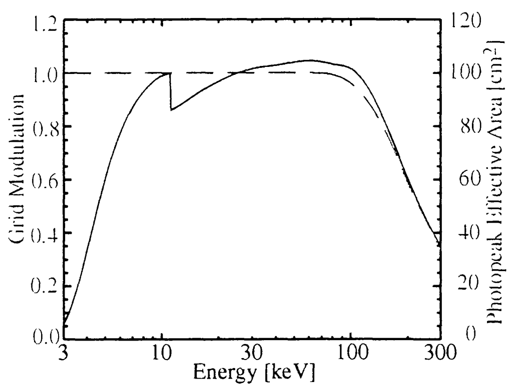

Figure 3. Cyclone*'s photopeak effective area (solid line), including the effects of detector efficiency, window transparency, and grid transmission. Also shown is the average grid modulation (dashed line).*

facilities, allowing imaging with a dynamic range of 100:1. (In-flight calibrations are expected to increase the dynamic range to 500:1.)

2.2. Detector Plane

The *Cyclone* detector plane array consists of 19 GeDs in individual modules (modified HESSI design) mounted in a single cryostat, and cooled to 77 K with 60 W of power by a single Sunpower M77C Stirling-cycle cooler. GeDs cover the entire hard X-ray/soft γ-ray energy range with the highest spectral resolution of any readily available detector technology. *Cyclone* utilizes commercially produced PerkinElmer ORTEC LO-AX GeDs, 6-cm diameter and 2.0-cm thick, with quasi-hemispherical electrode configurations for very low capacitance. The GeD thickness of 2.0 cm provides maximum efficiency up to 200 keV, while avoiding excess volume to minimize activation background. The total active detector area is 540 cm^2. A 0.3-μm boron p^+ electrode and a 250-μm beryllium cryostat window allows ample transparency for observations down to 3 keV.

3. INSTRUMENT PERFORMANCE

Figure 3 shows the overall photopeak effective area for *Cyclone*, determined by convolving the energy-dependent GeD photopeak efficiency and the angular- and time-averaged transmission of the grid pairs. Also shown is the average modulation efficiency, defined as the modulation amplitude of the grids for a typical off-axis source location, compared to perfect, opaque grids of zero thickness and equal slit and slat widths. The effective area is optimized (>100 cm^2) in the range 6-120 keV. Adequate area remains for performing X-ray imaging and spectroscopy down to 3 keV. The GeDs and grids were designed to have high efficiency up to the 158 keV ^{56}Ni decay line, and the GeD response remains significant above 200 keV.

Cyclone narrow line and continuum point source sensitivities are presented in Figures 4 & 5. Observations of narrow lines are relatively immune to systematic uncertainties in the background since they are seen with respect to the continuum immediately above and below them. For background-dominated observations of continuum sources, systematic uncertainties for most hard X-ray/γ-ray missions are on the order of 1%. An RMC system has no moving parts, and the same detector reads source and background repeatedly and rapidly in succession, so it avoids systematics associated with off-target pointing, moving masses, or nonuniform response in a position sensitive detector plane. The modulation period for even the coarsest grids is much faster than the spacecraft spin period, so that any effects of variations in the background with spin and orbital phase will be suppressed. We are confident of reaching at least the 0.2% level of control of background systematics with *Cyclone*, which, as a shielded instrument in an equatorial orbit, will have a much less variable

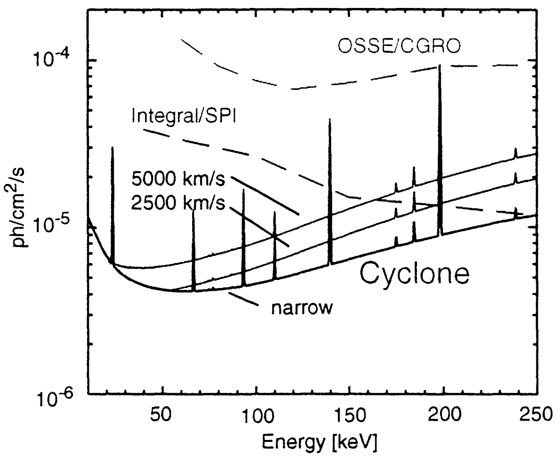

Figure 4. Cyclone*'s narrow line sensitivity (5σ, 10^6 sec), as well as the broad line sensitivities for 2500 km/s and 5000 km/s Doppler broadening. Shown for comparison are the narrow line sensitivities for Integral/SPI, and CGRO/OSSE.*

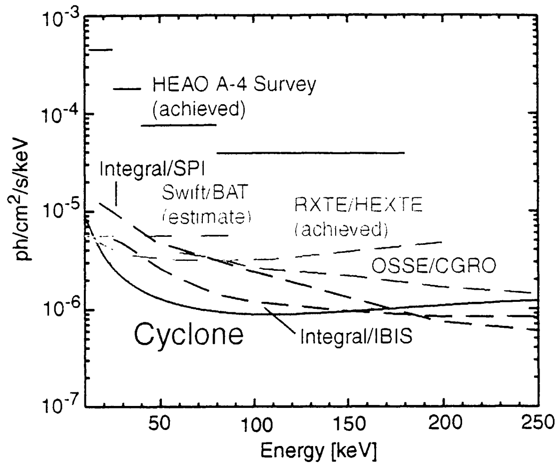

Figure 5. Cyclone*'s continuum sensitivity ($\Delta E = E/2$, 5σ, 10^6 sec). Low background, allows* Cyclone *to improve over much larger instruments.*

background than many previous missions. The sensitivities given in Figures 4 & 5, however, are achievable with even 1% systematic uncertainties.

4. MISSION

The *Cyclone* mission (Table 1) requires a simple spin-stabilized (60-s rotation) spacecraft, with the spin axis pointed at targets between 15° and 62° from the Sun (limited by solar array power), providing access to 88% of the sky over the course of the year. The 550-km circular, equatorial orbit can be provided by a standard Pegasus XL launch. Spacecraft pointing is relaxed ($< 0.5°$) and can be automated. Aspect is provided by redundant Advanced Stellar Compass (ASC) star trackers, developed at the Technical University of Denmark. The ASC can track attitude with 2" translational and 20" rotational precision at 4 Hz cadence, meeting *Cyclone* requirements. Typically, source pointings last 1-2 weeks, with the source eclipsed by the Earth 22-37% of each orbit, for pointing 62° and 0° off of the orbital plane respectively. All of the photon data collected for 24 hrs (even for the strongest sources) can be stored in the instrument mass memory. Consequently, *Cyclone* is planned for an automated store-and-dump operation, and no real-time access is required except for target-of-opportunity pointings. Both the instrument and spacecraft are designed to operate autonomously for weeks at a time. With no expendables, *Cyclone*'s lifetime could extend well beyond the 2-3 year nominal mission.

5. SUMMARY

Cyclone represents a major step forward in the evolution of hard X-ray/soft γ-ray astrophysics toward a narrow FOV, targeted observatory. The unprecedented combination of spectral resolution, angular resolution, and sensitivities make *Cyclone* a powerful observatory for studying nuclear line emission, SNRs, compact objects, the Galactic center, AGN, and other high energy sources. By addressing high-priority science while building upon readily available technologies and well-defined mission parameters (thanks to HESSI), *Cyclone* is ideally suited for the goals, timescales, and constraints of the NASA-SMEX program.

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