The Origin of Hard X-rays in M 17's Remarkable O4+O4 Binary

M 17, the closest Giant H II Region ($d \approx 2$ kpc), is a superior laboratory for the study of young massive stars. Producing the second-brightest H II region in the sky (after the Orion Nebula), the OB cluster NGC 6618 has nearly 10,000 members extending up to masses $M \approx 60 M_\odot$ (spectral type O4 V) in the central binary. It is a scaled-up, edge-on version of the Orion Molecular Cloud: a blister nebula on the edge of one of the Galaxy's most massive giant molecular clouds. With an age of ~ 0.5 Myr (Hanson et al. 1997, ApJ 489, 698) and no evolved stars, M 17 is one of the few massive star-forming regions whose massive stars are luminous enough to produce a prominent X-ray outflow (Townsley et al. 2003, ApJ 593, 874) and yet is unlikely to have hosted any supernovae.

Co-I's Townsley and Garmire have amassed 320 ks of *Chandra* ACIS-I time on NGC 6618, through a combination of GO and ACIS GTO programs, to study M 17 and its enormous X-ray champagne flow. The ACIS data reveal that the massive O4 stars in NGC 6618 are a pair of remarkable hard, variable X-ray sources separated by 1.8″ (Broos et al. 2007, ApJS 169, 353; Fig. 1A). The stars are seen through $A_V \approx 10$ mag and no spatially resolved near-infrared photometry or spectroscopy of the visual pair is published. The pair is known historically as Kleinmann's Anonymous Star (Kleinmann 1973, ApL, 14, 39); Chini et al. (1980, A&A, 91, 186) describe their unresolved source "CEN 1" as a pair of early O stars and report a combined spectral type of O4. Similarly the infrared spectrum of Hanson et al. (1997) does not resolve the pair.

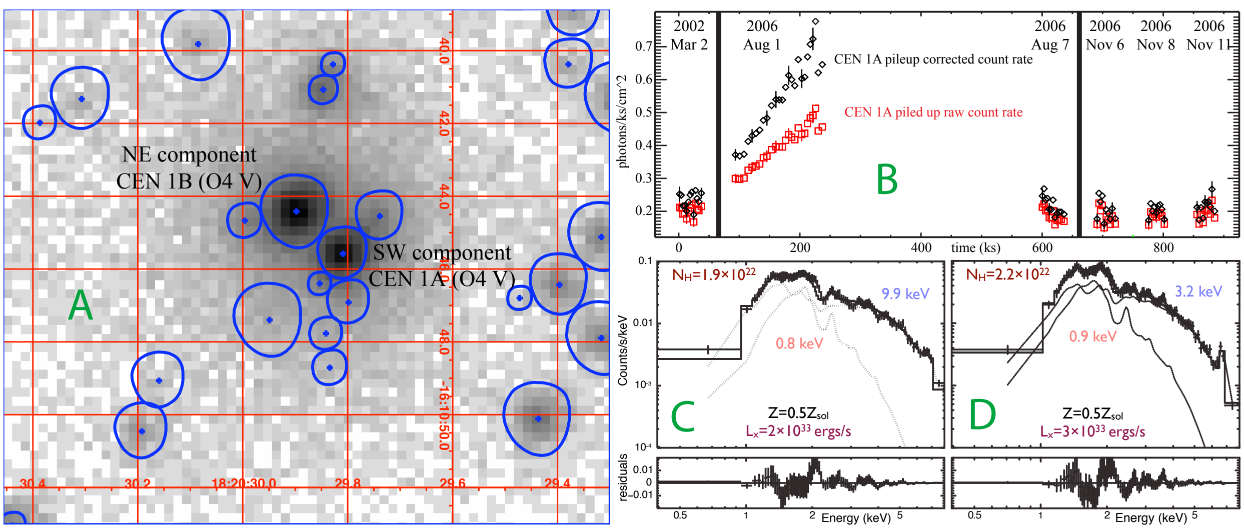

Figure 1: **Panel A:** ACIS-I image in the 14″ × 16″ core of M 17. The two O4 stars CEN 1A and CEN 1B are separated by 1.8″. **Panel B:** CEN 1A (O4 V) raw and pileup-corrected light curves. Solid vertical lines represent long data gaps. Pileup-corrected ACIS-I spectra of CEN 1B (**panel C**) and CEN 1A (**panel D**) for the last ∼50 ks of the 2006 Aug 1-2 observation.

ACIS clearly resolves these stars and shows unusually hard X-ray spectra for each component. A contiguous 150-ks ACIS observation in August 2006 showed that CEN 1A, usually the fainter of the pair, brightened by a factor of 2 over the course of 2 days, completely unexpected behavior for a young, massive star (Fig. 1B). As it brightened, CEN 1A went from minimally-piled to substantially piled; here photon pile-up suppresses the amplitude of the brightness variations, so the apparent lightcurve is distorted. Co-I Broos has devised a new method for reconstructing an unpiled spectrum (Fig. 1C) and lightcurve (Fig. 1B) for a piled-up source, using forward modeling with Monte Carlo simulations. The results of the XSPEC APEC fits to the reconstructed CEN 1B and CEN 1A spectra are shown in Fig. 1C and D.

Once corrected for pile-up, we see that CEN 1A actually rose in brightness by a factor of *three* in

2 days (Fig. 1B), to an intrinsic full-band luminosity of 3×10^{33} ergs s^{-1}, then dropped back to its low state 4 days later. Its soft spectral component is typical of O-star X-ray emission but it also shows an unusual hard component (Fig. 1D). The time-integrated CEN 1A spectrum (320 ks) shows an emission line near 6.5 keV. CEN 1B also shows the normal soft thermal component but exhibits an extraordinarily hard component, with $kT_2 \approx 10$ keV (Fig. 1C).

We propose here a 175 ks HETG observation of M 17's O4-O4 binary to explain the source of the hard X-ray emission from each of these stars. ACIS PI Gordon Garmire has contributed 25 ks of ACIS GTO time to this effort, thus we request 150 ks from the GO panel. The GTO time is contingent on the success of this GO proposal; we cannot achieve our science goals with the GTO time alone, so if the GO proposal is not approved we will relinquish the GTO time.

Sources of Hard X-ray Emission in Massive Stars

To our knowledge, there are four known classes of hard, time-variable X-ray sources associated with very massive stars: (1) high-mass X-ray binaries including Be X-ray binaries, (2) the enigmatic Be stars like γ Cassiopeiae, (3) magnetic hot stars like θ^1 Orionis C, and (4) colliding wind binaries like η Carinae. The stars in M 17 cannot be HMXBs or Be stars because they are too young. If the X-rays from CEN 1A and/or CEN 1B are produced by magnetically channeled wind shocks (MCWS), these would be the most massive stars to date with strong magnetic fields. If the X-rays are produced in the wind interaction zone of close binaries, they would be the youngest known colliding wind-shock (CWS) binaries and the only known visual pair of CWS binaries. They would also be the only known CWS binaries that do not contain a Wolf-Rayet star or a Luminous Blue Variable. Either result (MCWS or CWS) would represent a significant step forward in our understanding of the evolution of mass loss and magnetic fields on the highest-mass stars.

A mystery is starting to emerge from *Chandra* observations of massive young stellar clusters: while hard X-rays from very young O stars have been seen in other massive young clusters (e.g., in the Orion Nebula Cluster – Gagné et al. 2005, ApJ, 628, 986, in W3 – Feigelson & Townsley 2008, ApJ 673, 362, and in NGC 3576 – Townsley 2006, astro-ph/0608173), hard X-rays from O stars are *not* seen in clusters aged > 2 Myr (e.g., Schulz et al. 2003, ApJ, 595, 365). The mechanism generating hard X-rays in massive cluster seems to die away quickly, only to reappear in the most massive, highly evolved stars.

To advance our understanding of this new class of young O stars with hard X-ray emission, we propose a long grating observation of the core of M 17 to obtain spatially resolved, simultaneous X-ray grating spectra of the twin O4 stars CEN 1A and CEN 1B. Our simulations show that each star will produce sufficient S/N in 175 ks to yield high fidelity measurements of three He-like forbidden-to-intercombination line ratios, $\mathcal{R} = f/i$, thereby providing a direct test of both the MCWS and CWS scenarios.

Specifically, in MCWS simulations (ud Doula & Owocki 2002, ApJ, 576, 413; Gagné et al. 2005) the shocks are produced within a few stellar radii of the photosphere where the magnetic field is strong enough to confine the wind. MCWS theory predicts *low* $\mathcal{R} = f/i$ ratios because the strong far-UV flux from the photosphere depopulates the upper level of the forbidden line in He-like ions like S XV, Si XIII and Mg XI.

The rapid variability seen in CEN 1A, however, is difficult to explain with the MCWS model. The large rise seen in Fig. 1B is more reminiscent of the colliding wind shocks in highly elliptical systems. Although very hard X-rays, Fe Kα emission, and a large-amplitude rising light curve have been observed on η Car (Corcoran et al. 2004, ApJ 613, 381), the rise of η Car occurs over a period of months (not days), and both components of η Car are extremely luminous, highly evolved stars. The X-ray rise occurs as the stars approach periastron in a highly eccentric 5.5-year orbit because, to first order, L_X increases as the inverse of the binary separation (Antokhin, Owocki, & Brown 2004, ApJ, 611, 434). In addition, shorter-term variations of up to 25% are seen in the *RXTE* light curves of η Car.

Although CEN 1A and 1B are not known to be spectroscopic binaries, CWS emission would occur in the wind interaction zone between the binary components. If the X-rays are produced by CWS, CEN 1 would be a hierarchical, quadruple early-O system. Typically, high-mass binaries have orbital periods of weeks to years, placing the wind interaction zone at least $10R_\star$ from either photosphere. Thus, we expect CWS to produce *high* $\mathcal{R} = f/i$ ratios in high-Z ions like S XV, Si XIII and Mg XI.

We acknowledge that, spectroscopically, the f/i ratios alone cannot distinguish between MCWS and CWS if the wind interaction zone is *very* close to one O4 photosphere. However, very low f/i ratios in a CWS system requires a very close binary orbit. For example, for a system mass $M_1 + M_2 = 80M_\odot$ and a stellar radius $R = 10R_\star$, a separation of $10R_\star$ implies an orbital period of only 4 days. Our long series of ACIS-I observations in 2002 and 2006 discovered one rapid rise in CEN 1A and none in CEN 1B. We are confident that the combination of long observations and spectroscopic diagnostics will allow us to determine if either star is indeed a CWS binary. We note, as well, that near-infrared spectroscopy can be used to detect close spectroscopic binaries.

If the hard X-rays from CEN 1A and CEN 1B are produced by CWS, this result would have important implications for the formation and evolution of massive star clusters. Giant molecular clouds may form large numbers of close, high-mass binaries that coalesce into even higher mass stars. On the other hand, MCWS emission would suggest that strong fossil magnetic fields may be present in many young, massive stars. It is not clear how those magnetic fields cause rapid, large-scale X-ray variability (as already seen on CEN 1A) or how those strong fields disappear in most older O stars. Either way, the proposed experiment will allow us to determine how X-rays are produced on this remarkable pair of massive stars. We believe this experiment is astrophysically important and makes excellent use of *Chandra*'s unique capabilities.

Feasibility and Observing Strategy

The primary goal of the proposed grating observation is to determine the origin of the X-ray shocks on the two O4 stars. Although well resolved in the ACIS-I image (Fig. 1A), a grating observation will require a relatively tight roll angle constraint of $135 \pm 15°$ in order to resolve events and separate the dispersed HEG and MEG spectra of each star. Our simulations show that with a roll angle within these tolerances, the standard CIAO tools tg_resolve_events and tgextract can nearly completely separate events from each source, despite the fact that the spectra are fewer than 4 *Chandra* pixels apart. Outside these roll angle-limits, the spectra begin to overlap. This $120 - 150°$ roll-angle constraint can be met during an 18-day interval in June 2009, from day 3987 to 4005 (approximately 6.7 *Chandra* orbits). In order to achieve our science goals, we think the proposed hard roll constraint is well justified given the significant 175-ks exposure time request.

Detailed MARX simulations confirm that the proposed science goals can be achieved in a total exposure time of 175 ks (150 ks requested from this panel). The pile-up-corrected ACIS-I spectra were fit with a two-temperature APEC plasma in XSPEC. The column densities of CEN 1A and 1B for all times were 2.2 and 1.9×10^{22} cm^{-2}, respectively. For both stars, the median best-fit temperature for the cool component was 0.9 keV. The median best-fit temperatures for the hot components were 3.8 and 7.4 keV for CEN 1A and 1B, respectively. The median cool and hot normalizations for CEN 1A and 1B were 3.0 and 1.0, and 3.8 and 1.8×10^{-3} cm^{-5}, respectively. For CEN 1A, a Gaussian line at 6.5 keV was required to achieve a good fit.

The emergent photon flux at Earth was synthesized with a modified version of the ISIS code (Cohen et al. 2008, ApJ, in press: astro-ph 0802.4084) in which $\mathcal{R} = f/i$ and $\mathcal{G} = \frac{f+i}{r}$ are adjustable parameters. For the purpose of this feasibility study, we considered two limiting cases: an X-ray plasma at $4R_\star$ from the O4 photosphere (the MCWS scenario) and an X-ray plasma $\gg 4R_\star$ from the O4 photosphere (the CWS scenario). In the MCWS MARX simulations the stars were placed at their ACIS J2000 coordinates and the satellite roll angle was set at 135°. The resulting events files were reduced in CIAO 3.4 and HEG and MEG spectra were extracted for each star. These steps were repeated for the CWS simulations.

An ACIS-S image (Fig. 2 top) of a portion of the MEG grating arm shows that the spectra of CEN 1A and 1B will be cleanly resolved with a roll angle of $\sim 135°$. Fig. 2 (lower panel insets) show simulated HEG and MEG spectra around the three important He-like diagnostics: S XV, Si XIII and Mg XI. We fit the simulated spectra with HEGAUSS, a customized XSPEC module which implements a three Gaussian line emission model. HEGAUSS directly accounts for the covariance in the normalizations of each line by using $\mathcal{R} = f/i$ as an adjustable parameter. From the simulated CEN 1A data, we are able to determine $\mathcal{R}$ within 13% (90% confidence limits) for Si XIII and within 25% for S XV and Mg XI. This will achieve our primary science goal: to distinguish between the MCWS and CWS scenarios.

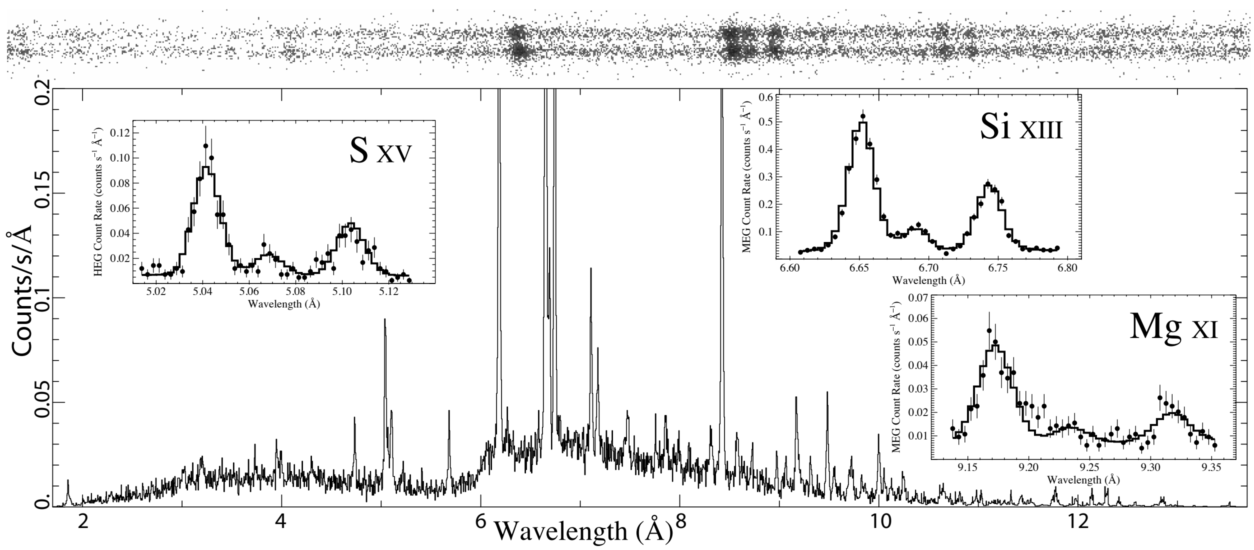

Figure 2: MARX+ISIS 175-ks simulation of CEN 1A and 1B. **Top panel:** Image of the MEG grating arms of both stars showing the Si XIV line and the Si XIII triplet between 5.5 and 7.5 Å. With an optimal roll angle of 135°, the spectra are separated by 4 ACIS pixels. **Lower panel:** 1.7–13.7 Å MEG spectrum showing strong continuum and prominent emission lines of H- and He-like Fe, Ca, Ar, S, Si, and Mg. Superposed are simulated data (points with error bars) around the three best He-like triplets in the CEN 1A HEG and MEG spectra: S XV near 5.1 Å, Si XIII near 6.7 Å, and Mg XI near 9.3 Å. The solid histograms show the best-fit HEGAUSS fits.

This experiment can only be performed with *Chandra* because the stars are separated by only 1.8″. Although grating astigmatism smears out spectra in cross-dipersion at long wavelengths, these sources are highly absorbed, producing essentially no flux beyond 14 Å. The HEG and MEG gratings are thus ideally suited for these hard X-ray sources.

The spectra will be of sufficient S/N to determine line widths and line centroids to < 50 km s^{-1} accuracy and line profile analyses will determine the asymmetry of the emission lines, thereby allowing us to probe shocks in the winds of these very young O4 stars. The simulated spectra also show resolved Fe XXVI and Fe XXV lines below 2Å, allowing us to probe the very hardest shocks on these young, very massive stars. If the Fe Kα line seen in the CCD spectrum of CEN 1A is real, it will be detected in the HEG spectrum.

Previous Chandra Programs: PI or Observer Marc Gagné

GO AO1, RHO OPH A (PI Gagné): Simultaneous *Chandra* and Very Large Array Observations of Young Stars and Protostars in ρ Ophiuchus Cloud Core A, Gagné, Marc, Skinner, Stephen L., Daniel, Kathryne J. 2004, 2004, ApJ, 613, 393

GTO AO1, Pleiades (PI Linsky, Observer Gagné): Observations of the Core of the Pleiades with the *Chandra* X-Ray Observatory, Krishnamurthi, Anita, Reynolds, Christopher S., Linsky, Jeffrey L., Martín, Eduardo, Gagné, Marc 2001, AJ, 121, 337

Chandra Observations of the Pleiades Open Cluster: X-Ray Emission from Late B- to Early F-Type Binaries, Daniel, Kathryne J., Linsky, Jeffrey L., Gagné, Marc 2002, ApJ, 578, 486

GTO AO2, M16 (PI Linsky, Observer Gagné): *Chandra* Observations of the Eagle Nebula. I. Embedded Young Stellar Objects near the Pillars of Creation, Linsky, Jeffrey L., Gagné, Marc, Mytyk, Anna, McCaughrean, Mark, Andersen, Morten 2007, ApJ, 654, 347

Chandra Observations of the Eagle Nebula. II. High-Mass Stars and a Census of NGC 6611, Marc Gagné, Anna Mytyk, Matthew Young, Mark McCaughrean, Morten Andersen & Jeffrey L. Linsky, in preparation

GO AO2, NGC 2024 (PI Skinner): A Deep Chandra X-Ray Observation of the Embedded Young Cluster in NGC 2024, Skinner, Stephen, Gagné, Marc, Belzer, Emily 2003, ApJ, 598, 375

GO AO3, HD 37022 (PI Gagné): *Chandra* HETGS Multiphase Spectroscopy of the Young Magnetic O Star θ^1 Orionis C, Gagné, Marc, Oksala, Mary E., Cohen, David H., Tonnesen, Stephanie K., ud-Doula, Asif, Owocki, Stanley P., Townsend, Richard H. D., MacFarlane, Joseph J. 2005, ApJ, 628, 986

GO AO4, M8 (PI Gagné): Deep Inside the Lagoon Nebula, Castro, P. J., Gagné, M., Tothill, N. F., Kenworthy, M. A., McCaughrean, M. J. & Stecklum, B. 2008, in preparation

GO AO8, AFGL 4029 (PI Gagné): OBSID 7443 observed 2007-11-20

GO AO9, G305 (PI Gagné): OBSID 8922 scheduled 2008-12-13.