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ULTRAVIOLET CONTINUUM VARIABILITY AND VISUAL FLICKERING IN THE PECULIAR OBJECT MWC 560

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ABSTRACT

High-speed U-band photometry of the peculiar emission object MWC 560 obtained with the ground-based instrumentation, and V-band photometry obtained with the *International Ultraviolet Explorer* (*IUE*)–Fine Error Sensor (FES) indicates irregular brightness variations are quasi-periodic. Multiple peaks of relative brightness power indicate statistically significant quasi periods exist in a range of 3–35 minutes, that are superposed on slower hourly varying components. We present a preliminary model that explains the minute and hourly time-scale variations in MWC 560 in terms of a velocity-shear instability that arises because a white dwarf magnetosphere impinges on an accretion disk. We also find evidence for Fe II multiplet *pseudo-continuum* absorption opacity in far-UV spectra of CH Cygni which is also present in MWC 560. Both CH Cyg and MWC 560 may be in an evolutionary stage that is characterized by strong UV continuum opacity which changes significantly during outburst, occurring before they permanently enter the symbiotic nebular emission phase.

Subject headings: stars: emission-line, Be — stars: individual (MWC 560) — techniques: photometric — ultraviolet: stars

1. INTRODUCTION

MWC 560 is a peculiar emission object that has had a history of unusual photometric and spectroscopic behavior. It is considered *symbiotic-like* because of the presence of TiO absorption and infrared blackbody emission (IRAS 07233−0737) appropriate to an M4e-M5e giant, and prominent Balmer line emission (Sanduleak & Stephenson 1973). The observational properties of MWC 560 have been described recently by Buckley (1992). During the 1990 photometric-spectroscopic outburst, absorption features present in broad wings of Balmer emission lines exhibited violet displacements in excess of -6500 km s^{-1} (Tomov 1990; Tomov et al. 1992). Outflow speeds of this magnitude exceed by a factor ~ 2–3 the maximum velocities associated with ejecta in classical novae, and suggests unusually high energetic processes that are also not typical of symbiotic novae in outburst (cf. Kenyon 1986).

Far-UV spectra obtained with the *International Ultraviolet Explorer* (*IUE*) indicate the presence of a hot UV continuum source that is heavily veiled by absorption from singly ionized metals, particularly Fe II, which determines the UV-continuum flux distribution in the 1200–3200 Å range. During the 1990 outburst when the system was ~ 2.2 mag brighter compared with its 1984 March level of $m_v \sim 11.4$ mag (Bond et al. 1984), broad *pseudo-continuum* absorption features that correspond to minima in the UV continuous metallic opacity showed violet displacements of ~ -6000 km s^{-1} (Michalitsianos et al. 1991). This is explained by the flow of an optically thick wind in the presence of an extremely steep velocity gradient.

Although MWC 560 has been followed quite closely since the 1990 outburst, its nature remains obscure. In addition to its unusual spectroscopic properties, MWC 560 also shows persistent irregular brightness variations of ~ 0.1–0.2 mag that occur on time scales of days, hours, and minutes. An analysis of high-speed visual photometry indicates the irregular light fluctuations observed contain quasi-periodic components that occur on time scales of hours and minutes, similar to that seen in cataclysmic variables (CVs) (Bruch 1992), and to quasi-period photometric variations observed in the symbiotic star CH Cygni (Slovak & Africano 1978; Hack & Selvelli 1984).

2. HIGH-SPEED PHOTOMETRIC OBSERVATIONS AND DATA ANALYSIS

Ground-based photometry was obtained on 1992 February 26 continuously for 4.5 hr using the Johnson U-band filter. Observations were obtained continuously for 4.5 hr in separate channels (Fig. 1*a*) with a 2 s integration time using the McDonald 0.76 m telescope two-channel offset guider-photometer.

High-speed photometric observations were also acquired with the *IUE* (Fig. 1*b*, 1*c*) using a novel application of the Fine Error Sensor (FES). As a high-speed optical photometer the FES can achieve a time resolution of ~ 100 ms and a relative photometric accuracy of $\delta v \sim 0.01$ mag per sample run with excellent photometric stability. The spectral response of the FES S-20 photocathode of 4000–7000 Å has greater relative sensitivity shortward of 5000 Å. The conversion of FES counts to V-magnitude is given by Perez (1991).

The Horne & Baliunas (1986) periodogram of the McDonald U-band photometry (Fig. 1*d*) shows multiple broad peaks corresponding to periods or quasi periods that range from

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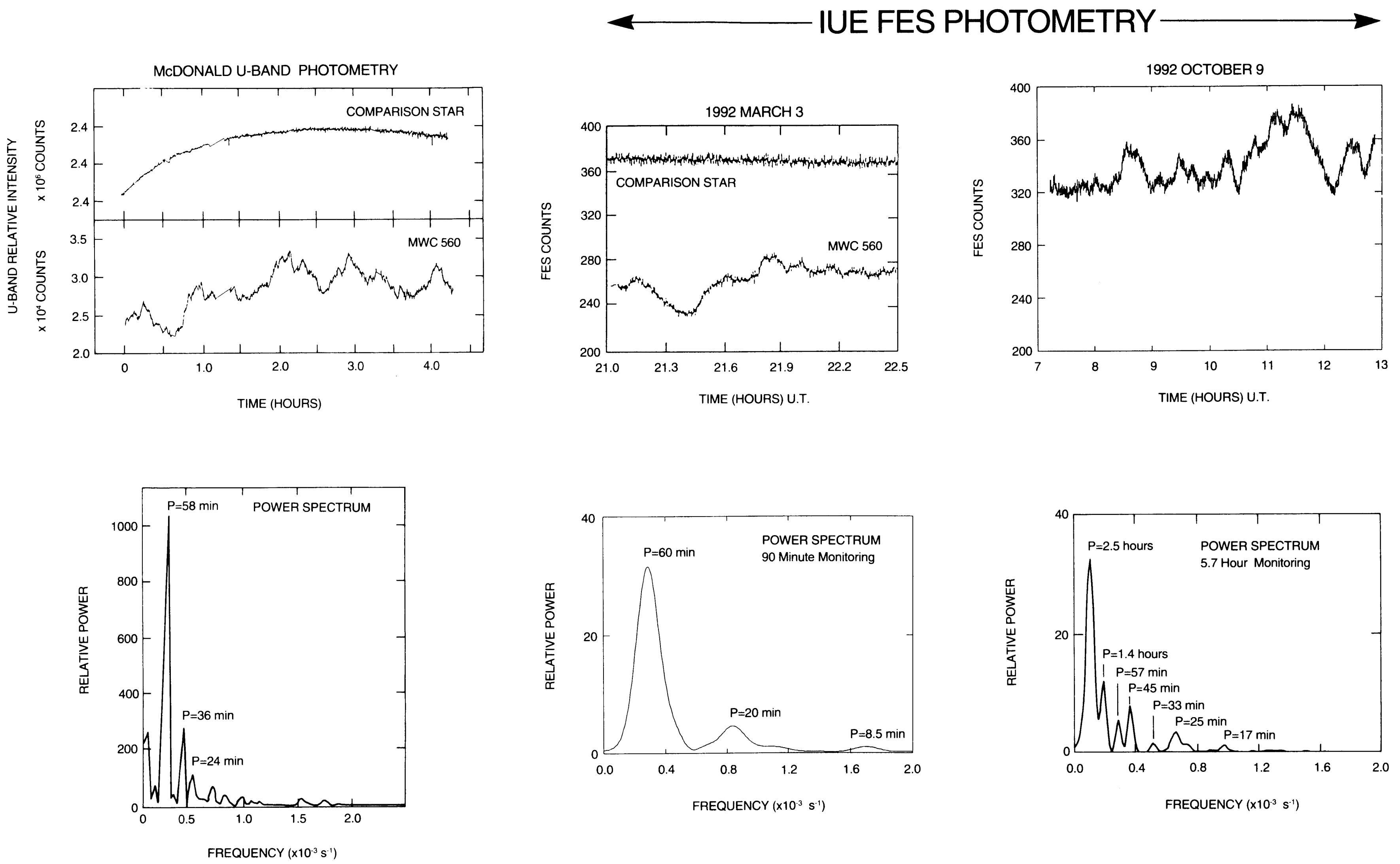

FIG. 1.—High-speed *U*-band photometry obtained with the McDonald 0.76 m telescope two-channel offset guider-photometer, and two separate *V*-photometry data sets obtained with the *IUE*-FES. (*a*) McDonald Observatory 4.5 hr monitoring of MWC 560 in the *U*-band obtained 1992 February 26. Short gaps in the data are the result of sky background observations. The comparison star shows only systematic variations because of the changing air mass. Variations on time scales of ~1 hr and on minutes are evident. (*b*) 90 minute continuous *V*-band (4000–7000 Å) photometric monitoring with the *IUE*-FES of MWC 560 obtained on 1992 March 3. Comparison is made with HD 155311 (A0, $V = 9.2$ mag obtained on 1992 April 17 during a 100 minute spectral observation of Nova Oph 1988). The data of MWC 560 are averaged in 10 s resolution bins, after removing all systematic effects including spacecraft jitter. Variability on similar time scales are evident between the McDonald and 90 minute FES data sets. (*c*) 6 hour continuous monitoring of MWC 560 with the FES on 1992 October 9. The individual data points are separated by 100 ms and are averaged in 10 s bins. The FES counts obtained were on average 60 counts (~0.2 mag) greater compared with the 1992 March 3 observations (90 minute data set). Hourly and minute time-scale variations are present. (*d*) Periodogram of McDonald 0.76 m *U*-band photometric data acquired obtained using the Horne & Baliunas (1986) period search program. The first and second half of the data set were analyzed separately which revealed statistically significant peaks at 58 ± 1, 35±, and 24 ± 1 minutes; the 3 and 10 minute periods are probably less significant. (*e*) Periodogram of the 90 minute FES data set using the unequal interval FFT plus CLEAN algorithm and a Scargle periodogram routine. Statistically significant power is indicated at 60, 20, and 8.5 minutes, consistent with those found in the ground-based data set. (*f*) Periodogram of the 6 hr FES data set obtained using the FFT and CLEAN algorithms, and averaging the data in the same manner as in the 90 minute FES data set. The 5.7 hr continuous monitoring of this data set achieves a factor of 3.8 increase in frequency resolution compared with the shorter 90 minute data set, enabling us to resolve the 60 minute period into additional components of 1.4 hr and 45 minutes. The 2.5 hr variation is correlated with the largest amplitude fluctuations present in the data set, but may not be periodic.

several minutes to ~1 hr. Analysis of the first and second half of the data set separately indicates that statistically significant peaks correspond to periods of 58 ± 1, 35 ± 1, and 24 ± 1 minutes; smaller peaks of less statistical significance with periods ranging from 3 to 10 minutes were detected in both first and second half data sets that we have analyzed separately.

The FES photometric data were analyzed using the unequal-interval FFT plus CLEAN algorithm and Scargle periodogram routines. We obtained the power spectrum of the entire 90 minute data set (Fig. 1*e*). The periodogram indicates a dominant variation occurs on a ~60 minute time scale, which is similar to that found with ground-based *U*-band photometry. Variations of 10%–20% on a time scale of 20 minutes to ~1 hr appear in both ground-based and satellite data sets and include additional rapidly varying components on time scales of 3–35 minutes that are superposed on the slower brightness variations. The peaks found in the periodogram appear quasi-periodic because of their broad bandwidths, that is, the 57 minute period has a bandwidth FWHM $\Delta\nu/\nu = 0.26$. The ~1 hr quasi-period modulation observed with the FES might be suspect as a bias in the periodogram method because it is comparable with length of the 90 minute long data set. However, the presence of statistically significant power at this period from the McDonald photometry *independently* argues that this modulation is real. More recent FES photometry data obtained over ~6.0 hr (Fig. 1*c*) that achieves greater frequency resolution by a factor ~3.8 compared with the 90 minute data set (Fig. 1*b*), also indicates a 57 minute modulation (Fig. 1*f*). Moreover, additional multiple peaks at 80, 57, and 45 minutes are also resolved (Fig. 1*f*) in this data set. The lowest frequency peak of 2.5 hr simply reflects the largest correlated variations accessible from the 6 hr data set; it is likely that none of these observed time scales are truly periodic. In addition, the amplitude of a peak in the periodogram decreases as the frequency increases. This may be the signature of *1/f-noise*.

3. FAR-UV SPECTROSCOPY

Similarities between MWC 560 and CH Cygni appear in the character of the 1200–2000 Å spectroscopic variations obtained with *IUE*. MWC 560 exhibited deep broad absorption features during outburst in the violet wings of the Balmer lines (Hα through H_{20}) which were blueshifted to velocities that peaked in excess of ~ -6500 km s^{-1}, consistent with the escape velocity of a white dwarf. High-velocity activity was also recorded with *IUE* during this phase. Strong metallic absorption bands that dominate SWP 1200–2000 Å spectra that are attributed mainly to singly ionized metals of Fe II, Cr II, Mn II, Si II, and Mg II, and showed blueshifts that ranged up to ~ -6000 km s^{-1}. The outburst in MWC 560 is characterized by large changes in the integrated $F_{\rm uv}$ flux that is reflected in changes in Fe II absorption band structure. An increase in ionization was not seen in the far-UV or visual, as evident by the complete absence of high excitation permitted, intersystem, or forbidden-line emission during outburst.

The high-speed outflow activity in MWC 560 culminated with the decline in the integrated 1200–3200 Å flux, $F_{\rm uv}$, by roughly a factor ~5, particularly at wavelengths at $\lambda \leq 1400$ Å. The decrease in $F_{\rm uv}$ was accompanied by a drop in the visual flux by ~0.5 mag. We have used an LTE uniform density isothermal slab model to estimate the column density of intervening material required to produce the observed UV fading (Shore & Aufdenberg 1993). We assumed solar abundances, an electron density of 10^8 cm^{-3}, and an electron temperature of $T_e = 7000$ K. These conditions correspond to the iron absorption spectrum that dominates the far-UV (Shore 1993a). A hydrogen column density of $N_{\rm H} \sim 10^{23}$ to 10^{24} cm^{-2} is required to reproduce the observed $F_{\rm uv}$ flux distribution during the *optically-thick phase*. During this phase the $F_{\rm uv}$ closely resembled that of a classical nova a few days after maximum visual light, when the density of the shell was a factor ~100 greater compared with $N_{\rm H}$ estimated for the *peculiar Be star phase* (Maran et al. 1991). It is important to note that the hot source cannot be completely covered. For an optically thick shell completely surrounding the hot source we should observe bolometric redistribution of flux, that is, the optical flux should vary in antiphase with the UV (Shore 1993b). This is not observed, and consequently a slab model is the most appropriate geometry used. The transformation of the UV spectrum of MWC 560 from one that resembled a peculiar Be-type star (Michalitsianos et al. 1991) to one that closely matched the spectrum of a classical nova in its optically thick phase (Maran et al. 1991)—and a return to the peculiar Be-star phase about 1 year later—indicates a much larger quantity of material is involved in the mass ejection process in MWC 560 compared with its symbiotic counterpart.

Changes in $F_{\rm uv}$ appear to be controlled by large variations in column density associated with an extremely thick UV absorbing foreground region. Outflow appropriate to these large column densities corresponds to mass-loss rates $\dot{M} \sim 10^{-5}$ to 10^{-4} $M_\odot$ yr^{-1}. Similar spectroscopic behavior has been seen in the prototypical symbiotic star CH Cygni which exhibited dramatic changes in $F_{\rm uv}$ following its 1984 outburst; this activity culminated in the appearance of strong nebular line emission and a bipolar radio jet (Taylor, Seaquist, & Kenyon 1988). Mikolajewska, Selvelli, & Hack (1988) found that the $F_{\rm uv}$ prior to the 1984 outburst was best matched with the continuum emission of an A-F type supergiant, based upon Kurucz model atmospheres, that includes contributions from optically thin free-free (ff) and free-bound (fb) nebular emission.

Figure 2 compares low-resolution ($\Delta\lambda = 6$ Å) SWP spectra of CH Cygni (SWP 15590, 1981 November 29) 3 years before outburst (top panel) with MWC 560 (SWP 39711, 1980 September 26) during the *optically thick phase* (bottom panel). The spectral features characteristic of this form of UV-continuum opacity include a broad *pseudo-emission* feature centered at $\lambda = 1500$ Å, and a relatively narrow feature at $\lambda = 1590$ Å. Both correspond to locally transparent wavelength regions associated with material which is dominated by absorptions from blends of singly ionized metals. These *pseudo-emission* features are also present in CH Cygni 3 years before outburst, which suggests the $F_{\rm uv}$ was also dominated by strong metallic line absorption, particularly Fe II, that obscured the underlying white dwarf and accretion disk. The presence of a few strong resonance and intersystem emission lines, that is, C IV, He II, O III], that are superposed on the *pseudo-continuum* in CH Cygni (Fig. 2, top panel) suggests the column density is generally smaller compared with MWC 560, or that the covering is not as large. Strong metal absorption probably explains why Kenyon & Webbink (1984) find that a simple combination of a hot stellar photosphere and ff-fb emission does not reproduce the observed $F_{\rm uv}$-continuum in CH Cygni. Moreover, Mikolajewska et al. (1988) find the effective temperature $T_{\rm eff} \simeq 9000$ K they derive from fitting A-F supergiant Kurucz model atmospheres is too low to explain the observed Balmer continuum and emission lines in CH Cygni. This also implies the source was not completely covered.

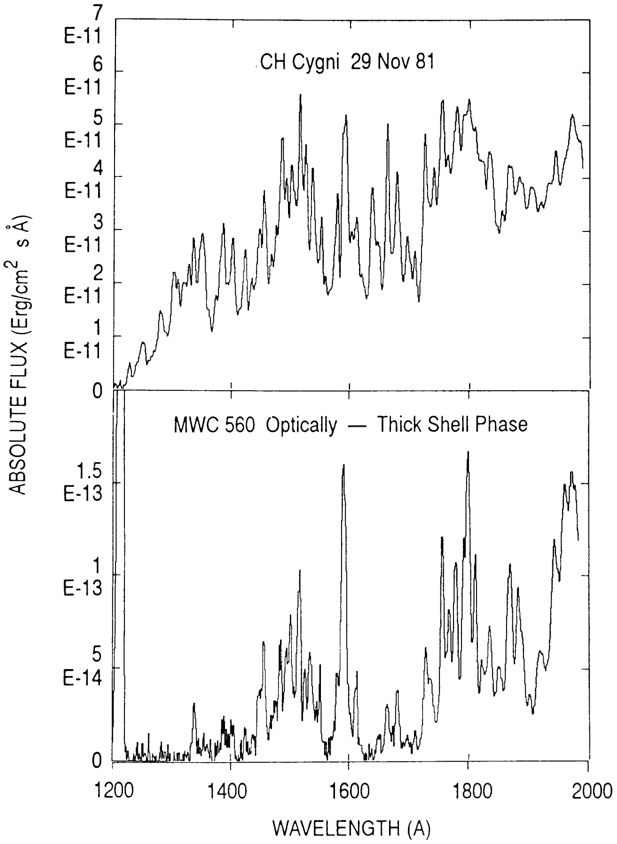

FIG. 2.—LORES (limiting spectral resolution $\Delta\lambda = 6$ Å) *IUE* spectrum obtained of CH Cygni approximately 3 years before a major outburst was observed in this system. Comparison is made with MWC 560 during the *optically-thick phase*. Both objects exhibit strong *pseudo-continuum* absorption opacity indicated by the distinct emission features which are formed by locally transparent wavelengths regions associated with material that is dominated by blends of Fe II absorption lines.

4. DISCUSSION AND CONCLUSIONS

Flickering in CVs is believed to result from instabilities associated with flow to an accretion disk or to instabilities in the polar accretion column (Livio 1993). However, with the exception of CH Cygni, flickering in symbiotic stars is virtually unknown. The disk in CH Cygni is fed by mass transfer from an M6-7 III giant through Roche lobe overflow. The accreting white dwarf is assumed to be magnetic, and consequently the inner edge of the disk corresponds to the outer edge of the magnetosphere; the hourly variations correspond to rotation of the accreting white dwarf.

The largest fraction of total energy available through accretion is emitted by viscous dissipation at the inner disk and magnetosphere boundary. This layer is susceptable to a velocity shear, or Kelvin-Helmholtz instability (Ghosh & Lamb 1982). The pressure of the magnetosphere is $B_*^2/4\pi$, where the stellar field is assumed dipole, and the pressure of accreting material $\rho_* v_*^2$; v_* is the infall velocity of material with a mass density of $\dot{M}/4\pi r_*^2 v_*$ for an accretion rate $\dot{M}$. Pressure equilibrium will occur at a radius $r_* = 0.13\ R_\odot$, that assumes a 10^6 G field appropriate for a normal white dwarf of mass $\sim 1\ M_\odot$, and radius 0.01 $R_\odot$, if $\dot{M} \sim 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$. The corresponding accretion luminosity is about 300 $L_\odot$, which is $\leq 10\%$ of the observed bolometric luminosity, for an $E(B-V) \sim 0.32$ and a distance of 2 kpc. For a 10^7 G magnetic field the equilibrium radius scales as

$$r_* = 10^{7.5}(B/1\ MG)^{4/7}(R/0.01\ R_\odot)^{12/7} \times (\dot{M}/10^{-7}\ M_\odot\ \mathrm{yr}^{-1})^{-2/7}(M/M_\odot)^{-1/7}\ \mathrm{cm}\ ,$$

so that r_* is roughly ~ 6 stellar radii. The period associated with a boundary layer oscillation excited by the velocity shear is $1/v_K \sim 140$ s, where v_k is the Keplerian frequency at r_*, and $k \sim 1/r_*$ is the characteristic wave number. The photometric variations that range between 8 and 35 minutes in MWC 560, are reminiscent of visual fluctuations in CH Cygni, are consistent with this model. In MWC 560 the hourly variations may be associated with rotation of the accretion column near the white surface (Livio 1993). However, we cannot rule out longer time-scale fluid instabilities as its origin.

Finally, the F_{uv}-continuum structure in MWC 560 and CH Cygni indicates a region of extremely large column density that obscures the inner disk and hot compact star. The large variations that range by more than one order of magnitude in F_{uv} flux in MWC 560 and CH Cygni are consistent with changes in column density that range by more than about two orders of magnitude before and after outburst.

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