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THE DISCOVERY OF LOW-ENERGY X-RAY EMISSION FROM U GEMINORUM

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ABSTRACT

Strong X-ray emission in the 0.15–0.5 keV band has been detected from U Gem during optical outburst. The peak flux observed in the 0.15–0.5 keV range is 3.2×10^{-10} ergs cm^{-2} s^{-1} ($\sim 3 \times 10^{32}$ ergs s^{-1} at 100 pc). No soft X-ray emission was detected during the quiescent optical phase at a level which is at least 100 times less than the peak outburst flux. During outburst, the soft X-ray source appears to be highly variable on a time scale of a few hours, but this variability is consistent with orbital dependence for the limited data sample available. The origin of the soft X-ray emission is discussed.

Subject headings: stars: novae — stars: U Geminorum — X-rays: sources

I. INTRODUCTION

Dwarf novae have received considerable attention because of the complexity of their behavior, and, more recently, because of their similarity to the "classical" X-ray binary systems. Consequently, dwarf novae have frequently been predicted to be intense soft X-ray sources (e.g., Warner 1974). Until now only SS Cygni, among such stars, had been detected above 0.1 keV (Rappaport *et al.* 1974; Hearn, Richardson, and Li 1976; Heise *et al.* 1978; Margon *et al.* 1978; Cordova *et al.* 1978; Swank *et al.* 1978; Mason, Cordova, and Swank 1978). We report here that the A-2 experiment[1] on *HEAO 1* has observed a strong, variable 0.15–0.5 keV X-ray source coincident with the position of the dwarf nova U Geminorum. Weak 2–10 keV emission was also detected at the same location by Swank *et al.* (1978).

II. OBSERVATIONS

U Gem was visible to the *HEAO* experiment for a total of 6 days, between 1977 October 17 and 22. The time history of the X-ray source as seen by the 0.15 to 2.5 keV detector (denoted LED 1; for a full description see Rothschild *et al.* 1978) is shown in Figure 1, corrected for elevation in the field of view. The variable nature of the emission on time scales of hours is readily apparent. Figure 1 also depicts the optical light curve of U Gem. The optical star suffered an outburst on October 18.7 which persisted throughout the remainder of the *HEAO* observation. We note that no soft X-ray emission was detected before the onset of the optical outburst to a level which is a factor of 100 below the maximum flux seen.

The energy distribution of the counts detected in LED 1 is illustrated in Figure 2, which depicts data from the sighting on October 20.6 (Fig. 1). All the source counts are concentrated in the lower six channels of the 29-channel pulse-height analyzer. There is no significant change in this distribution among the three sightings which yield strong detections and where spectral data were available (October 19.7, 20.6, 21.5). Specifically, we can limit changes in the slope of the spectrum incident on the detector to within 20% at the 3 σ level. The limited number of data channels available precludes a meaningful discussion of the merits of different spectral models. However, to facilitate comparison with other observations, we have fitted the data to the distribution expected for a thermal bremsstrahlung spectrum (including an energy-dependent Gaunt factor; Kellogg, Baldwin, and Koch 1975). Temperatures in the range 100,000 to 300,000 K ($\sim$0.01–0.03 keV) can reproduce the data within the uncertainties, which include both statistical and systematic effects. Blackbody models yield temperatures which are -75% of this. Assuming model temperatures of this order, we find a flux of 3.2×10^{-10} ergs cm^{-2} s^{-1} in the 0.15–0.5 keV band for the highest count rate point in Figure 1 ($\sim 3 \times 10^{32}$ ergs s^{-1} at 100 pc; Warner 1976; Staufer, Spinrad, and Thorstensen 1978). The effective energy of the *HEAO* detector for the U Gem spectrum is $\sim$0.25 keV. The *time-averaged* 3 σ upper limit to the flux during outburst in the 0.5–2.5 keV band is 2×10^{-10} ergs cm^{-2} s^{-1} for a flat photon spectrum.

We have investigated the possibility that the counts observed are due to UV contamination by examining several *HEAO* scans of bright UV stars, among them λ Sco and γ Ori. No signal is seen from such stars, with upper limits which are more than an order of magnitude less than the count rate seen from U Gem. To reproduce the signal would require that U Gem have a UV flux totally incompatible with its optical spectrum. We conclude that the U Gem data cannot be due to UV contamination and must therefore be caused by soft X-rays.

During the strong sightings of October 20.4 and October 21.3, the experiment was in a data-collection mode which has 80 ms time resolution. The mean count

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[1] The A-2 experiment of *HEAO 1* is a collaborative effort led by E. Boldt of GSFC and G. Garmire of CIT with collaborators at CIT, JPL, UCB, and GSFC.

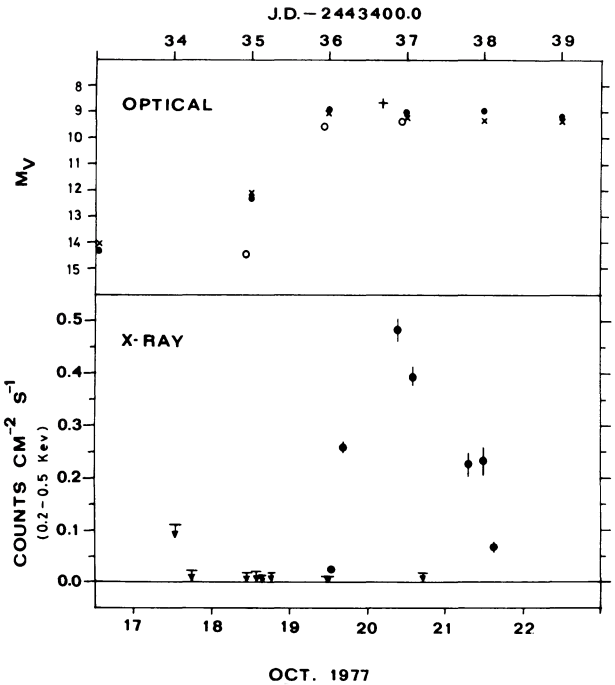

FIG. 1.—Time evolution of the soft X-ray flux of U Gem compared with its visual magnitude. During the U Gem observation, the *HEAO* low-energy detectors were being operated for only part of each day. Uncertainties in flux are dominated by the correction for the elevation of the source in the detector collimator. The optical magnitudes for the star were obtained from: ×, Morgan (1977); *closed circles*, the AAVSO (Mattei, private communication); *open circles*, Patterson (private communication); and +, the B.A.A. (Howarth, private communication).

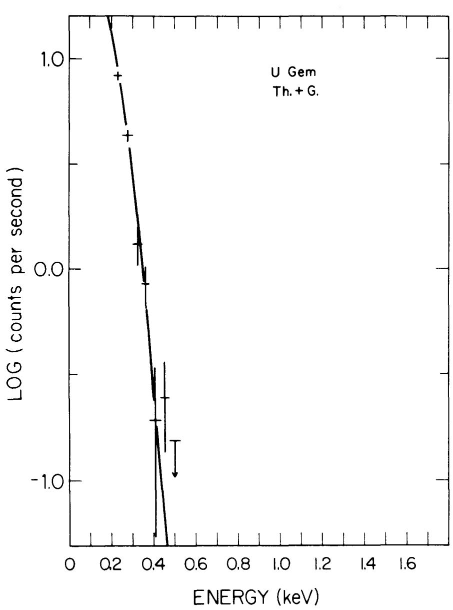

FIG. 2.—Count spectrum of U Gem as seen by the *HEAO 1* LED 1 detector during a ~15 s sighting on UT October 20.6. The predicted distribution for a thermal bremsstrahlung model (including Gaunt factor) with a temperature of 0.03 keV is shown as a solid line.

rate per 80 ms, corrected for collimator response in the scan direction, was ~10 and ~4, respectively, for the two sightings. We have searched these data for variability in excess of that expected from counting statistics, and find none on time scales between ~0.2 and a few seconds (the source transits the field of view in ~15 s). The upper limit to the fraction of the flux which is periodically pulsed on these time scales during the two scans is ~25% and 40%, respectively, at the 3 σ level. Patterson (private communication) has (fortuitously) obtained white-light photometric measurements of U Gem which were simultaneous with the *HEAO* sighting of October 20.4. His data, which were taken with a time resolution of 2 s, show that at this time the optical flux was constant to within about 1%.

Finally, we note that U Gem is a binary system with a period of 4.25 hours (Arnold, Berg, and Duthie 1976). To test the possibility that the variable signal observed is due to a binary effect, we have folded the soft X-ray data on the orbital period, as shown in Figure 3. The failure to detect a signal before October 19 cannot be explained by orbital dependence. However, most of the variability seen during outburst can be explained by supposing that the observed emission peaks at an orbital phase of ~0.85 (where phase 0.0 corresponds to the center of the quiescent optical eclipse). The fact that the shape of the X-ray spectrum is not a function of the strength of the source during outburst might also suggest that the intensity changes are an aspect effect. This apparent orbital relation, if confirmed, has important consequences for understanding the origin of the soft X-ray emission, but we stress that the data sample now available is too limited to exclude the possibility that the relationship is caused by fortuitous random variability.

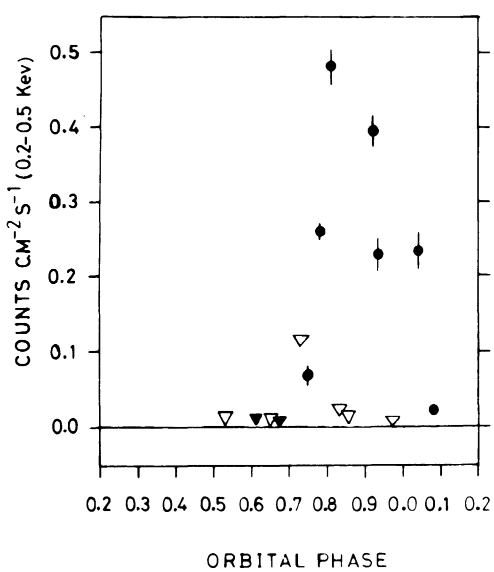

FIG. 3.—The *HEAO* soft X-ray data folded modulo the orbital period of U Gem. *Open symbols*, data taken before October 19.0; *closed symbols*, data taken after October 19.0 (see Fig. 1).

III. DISCUSSION

U Gem is the second dwarf nova system to have been definitely detected as an X-ray source. Like SS Cyg, U Gem is observed in the 2–10 keV range (Swank *et al.* 1978); unlike SS Cyg, U Gem has not to date been detected in either the hard or the soft X-ray band during its optically quiescent state (Novick and Woltjer 1975; Henry *et al.* 1975).

Dwarf novae are commonly thought to be close binary systems containing a white dwarf which is accreting material from a nondegenerate companion. Much of the quiescent optical emission comes from a bright spot which is formed by the impact of the gas flow on the accretion disk surrounding the white dwarf. The optical outbursts are probably brightenings of the accretion disk (Warner 1976; Robinson 1976).

There are two regions in such a system where one might expect a rate of energy release sufficient to produce X-radiation: (*a*) where the gas stream collides with the accretion disk; and (*b*) close to the white dwarf, where the accretion flow interacts with the surface of that star (e.g., Pringle 1977). There is sufficient kinetic energy in the accretion flow to produce a shocked region of the required temperature in the vicinity of the optical bright spot (Warner 1974). Further, we have shown that the X-ray emission may peak at an orbital phase when the bright spot faces the observer (e.g., Warner and Nather 1971). However, Pringle (1977) has argued that the optical depth of material surrounding the shock would be too great to allow low-energy X-ray photons to escape. It is also unclear why the X-ray source should be seen only during outburst, since the evidence available (e.g., Warner 1976) suggests that the accretion flow is affected very little by the latter. Indeed, the optical data indicate that during an outburst the accretion disk expands, so that the shock is less deep in the potential well of the white dwarf. The shock temperature should thus, if anything, decrease.

We have considered the possibility that the low-energy X-ray emission originates in an optically thin "coronal" region surrounding the binary system. Using the cosmic abundance X-ray emissivity code of Raymond and Smith (1977), we calculate from our data an emission measure $\int N_e^2 dV$ of $\sim 2 \times 10^{56}$ cm^{-3} at 100 pc. To explain the soft X-ray variability observed by periodic obscuration effects, the size of the emitting region must be smaller than the size of the accretion disk ($\sim 5 \times 10^{10}$ cm), which implies densities $> 10^{12}$ cm^{-3}. Alternatively, if the variability reflects the intrinsic behavior of the emission region, its time scale ($\tau \sim 3\ n_e V k T/L < 10^4$ s), in combination with our derived emission measure, constrains the mean density to be $\gtrsim 10^7$ cm^{-3} and the characteristic size to be $\lesssim 10^{14}$ cm. With the radiative loss function given, for example, by Cox and Tucker (1969), the total emission from this volume is $\sim 4 \times 10^{34}$ ergs s^{-1}. Because most of the emission falls below the range of the *HEAO* detectors, this number (and the value of the emission measure given above) depends critically on the instrument parameters used to fit the data as well as the assumed shape of the incident spectrum. It thus may admit to an uncertainty of up to a factor of 10. Nevertheless, it is clear that the total luminosity from such an optically thin cloud may be comparable to the integrated outburst luminosity (e.g., Warner 1976). At a temperature of $\sim 3 \times 10^5$ K, far-UV lines such as O VI λ1031 should be prominent (see Dupree 1975), and a search for these during U Gem outburst might constitute a sensitive test of the existence of this "corona."

A second class of possibilities involves soft X-ray emission from the immediate vicinity of the white dwarf. It cannot be photospheric radiation (of the kind seen, for example, in HZ 43), since the variability observed is much faster than the thermal cooling time scale for such a star. Also, the stability of the shape of the X-ray spectrum argues against the intensity changes being caused by varying absorption of a steady underlying continuum source. Accordingly, we consider source mechanisms which are variable through their dependence on accretion. One mechanism is emission from the boundary shock where the accretion disk grazes the surface of the white dwarf. Straightforward application of Pringle's (1977) calculations for a blackbody spectral temperature of 2×10^5 K and an X-ray luminosity of 3×10^{32} ergs s^{-1} yields a white-dwarf mass of $\sim 1.2\ M_\odot$ and an accretion rate of $\sim 10^{16}$ g s^{-1}. The optically thick boundary layer model, in its simplest form, does not account for the hard X-ray component observed by Swank *et al.* (1978), but it may be that only part of the emission region is optically thick, and that the hard X-rays are optically thin emissions from a different part of the boundary shock (Pringle and Mewe 1978).

An alternative explanation of the data is suggested by the calculations of Lamb and Masters (1978; see also Lamb 1978 and Ricketts, King, and Raine 1978), who compute the spectrum of a radially accreting magnetic white dwarf. In this model, the low-energy X-radiation observed by *HEAO 1* would be identified with blackbody emission from the surface of the white dwarf which is heated by hot ($T \sim 10^8$–10^9 K) bremsstrahlung and cooler (predominantly UV) cyclotron radiation from the shocked inflowing matter. Extrapolating from the measured low-energy spectrum and flux of U Gem and assuming it to be the tail of a blackbody distribution, we find that the total energy contained in this component must exceed $\sim 3 \times 10^{33}$ ergs s^{-1} (for $T_{\rm BB} \lesssim 2.5 \times 10^5$ K). The characteristic dimension of the blackbody emitting region is then $\gtrsim 3 \times 10^7$ cm. Since the total bremsstrahlung luminosity is only $\sim 10^{31}$ ergs s^{-1} (Swank *et al.* 1978), the cyclotron component must have a luminosity comparable to that of the blackbody emission, and may contribute significantly to the outburst flux at UV and optical wavelengths. Using the limits given above on the blackbody luminosity and temperature of U Gem, and following the prescription of Tuohy *et al.* (1978), we calculate that the cyclotron flux in the visible band would have $m_v \lesssim 13$, if the electron temperature in the postshock region is ~ 10 keV.

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