HIGHLIGHTS FROM THE HEAO-1 SURVEY OF CATACLYSMIC VARIABLE STARS

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Abstract

A survey of the x-ray properties of ~150 cataclysmic variable stars was conducted using the High Energy Astronomical Observatory, HEAO-1. U Geminorum was discovered to be emitting an intense soft x-ray flux and a weak hard x-ray flux during an optical outburst. Hard x-ray flickering was discovered from SS Cygni during optical quiescence. EX Hydrae, and possibly AY Lyrae, were detected in the soft x-ray band while in their quiescent states. Most of the cataclysmic variables evidenced no x-ray emission, including ~20 dwarf novae which were observed by HEAO-1 during optical outbursts. Finally, soft x-ray pulsations were discovered from SS Cyg and U Gem. Simultaneous visual coverage of the variable stars was provided chiefly by the American Association of Variable Star Observers (AAVSO) and the Royal Astronomical Society of New Zealand Variable Star Section (VSS).

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HEAO-1 was the first in a series of three satellites designed to make a comprehensive study of the high-energy universe. The specific mission of HEAO-1 was to conduct an all-sky survey of radiation ranging from the softest x-rays of 0.1 keV (thousand electron volts) to higher energy gamma rays of 10 MeV (million electron volts). (The time variability and spectra of the known x-ray sources could also be studied and, in addition, many new sources were likely to be detected with the increased sensitivity of the HEAO-1 detectors over previous x-ray instruments.)

HEAO-1 was launched Aug. 12, 1977, and continued to take data until Jan. 9, 1979. During the first six months of operation the satellite, (which was usually operated in a scanning mode) made a complete map of the x-ray sky. Later in the mission, the satellite was devoted mostly to pointings of several hours duration at selected targets to look for time variability.

Because x-rays had previously been detected from the dwarf novae, SS Cygni and AM Herculis, it was anticipated that other dwarf novae undergoing visual outbursts at the time they were being scanned by HEAO-1 might also show x-ray emission. Indeed, on the day HEAO-1 was launched Z Chamaeleontis, a prominent dwarf nova in the southern sky, was undergoing a "supermaximum." However, while the first HEAO-1 data showed many exciting new features in the x-ray sky, Z Cha was not one of them, nor was x-ray emission detected from several other dwarf novae, among them AH Herculis, AB Draconis, and CN Orionis, which also had eruptions while HEAO-1 scanned them in its first few weeks of operation. At the end of October, 1977, the first big surprise came.

On Oct. 18 we received a phone call at Caltech from the AAVSO informing us that U Geminorum was beginning an optical outburst. Many members of the AAVSO and the VSS (New Zealand) had volunteered to keep a vigil on the HEAO-1 program stars, and to alert us to sudden changes in the optical brightness of any survey star in the HEAO-1 scan path. The directors of these organizations, Mrs. Janet Mattei of the AAVSO and Mr. Frank Bateson of the VSS (New Zealand), coordinated this program and sent us the visual light curves of erupting dwarf novae for comparison with the x-ray light curves.

The data from the A-2 experiment, which was the experiment on HEAO-1 used for the survey, was shared by several institutions. The California Institute of Technology, the University of California at Berkeley, and the Jet Propulsion Laboratory in Pasadena, California, shared the low energy ("soft x-ray") data, while the Goddard Space Flight Center had charge of the high energy ("hard x-ray") data. For the week in which U Gem had an outburst, it was Berkeley's turn to process the low energy data. We immediately notified the Berkeley investigators of the U Gem outburst. However, a look at the Oct. 18 HEAO-1 data revealed no evidence of x-ray emission from a source at the position of U Gem. It appeared that this dwarf nova, like many others, was not an x-ray emitter.

So, imagine our surprise when the next day we received an excited call from the Berkeley group, telling us that an extremely bright source had suddenly appeared in the Oct. 19 data at the location of U Gem! Since the satellite was in a scanning mode at the time of this observation, it could only take a few 15-second "snapshots" each day. Hence there was no way to confirm whether the apparent day-long delay in the soft x-ray brightness (see Fig. 1) was due to a real lag in the turn on of the soft x-rays, or whether it was simply due to poor sampling of a highly variable soft x-ray source. Evidence for hard x-ray emission (Fig. 1) which appeared to peak with the visual brightening was also a surprise.

With this new discovery our hopes for the survey were renewed. In November, 1977, I went to Chile to use the 36" telescope at Cerro Tololo for observations of a few prominent cataclysmic variables which HEAO-1 was simultaneously scanning. Among these stars was VW Hydri, which happened to undergo both a supermaximum and a normal outburst while HEAO-1 observed it (Fig. 2). I also did photometry on RR Pictoris, the brightest of the ex-novae, and AE Aquarii, a very active nova-like object. I was dismayed to learn, upon my return to the States, that no x-ray emission had been detected from any of these stars! Why were some variables turning out to be x-ray sources and not others? Was it simply a distance factor, i.e., were SS Cyg and U Gem closer than the other cataclysmic variables? Or was the extremely low x-ray temperature of $\sim 2 \times 10^5$°K, telling us that these systems were too cool to be detectable as soft x-ray sources?

On Dec. 12, 1977, we had our first scheduled pointing at a cataclysmic variable: SS Cyg. Unfortunately, or so we thought at first, the dwarf nova was not undergoing an outburst at the time of the pointing. However -- another surprise -- hard x-ray emission with a temperature of $\sim 2 \times 10^8$K was detected from the dwarf nova. The hard x-rays were observed to flicker on a timescale of minutes. It was beginning to look as if the models for x-ray emission from cataclysmic variables would have to be revised; there had been no prediction of hard x-rays from systems believed to be undergoing non-radial accretion. The only theories involving hard x-ray emission required that the accretion be spherical or be "funnelled" by a magnetic field. This is the case, for example, in AM Her where a strong magnetic field is believed to funnel the material from a low mass red star onto "magnetic accretion poles" on the white dwarf (Tuohy et al. 1978 and references therein). Did the detection of hard x-rays from SS Cyg during quiescence imply that this dwarf nova also had a magnetic field which might disrupt the accretion disc at a radius close to the degenerate star? Pringle and Savonije (1978) then proposed an alternative to the magnetic white dwarf model, but without more hard x-ray data, particularly timing-data around the entire binary orbit of SS Cyg, it would be difficult to choose between the models.

The next few months were spent going over all the existing HEAO-1 x-ray data and superposing numerous scans for each day to see if any weak, new x-ray sources would emerge from the noise of the x-ray sky background. This technique was used to search for soft x-ray emission from the 150 stars in the Cataclysmic Variable Survey, but it showed no emission from ~20 dwarf novae which were undergoing optical outbursts during HEAO-1 scans. It also produced the first detection of soft (0.5-3 keV) x-ray emission from the dwarf nova EX Hydrae during optical quiescence, and a possible detection of very soft (0.15-0.43 keV) x-rays from the dwarf nova AY Lyrae, also during quiescence. Both of these sources showed evidence for "self-absorption," causing us to suspect that the large mass of the accreting cloud in these kinds of systems might be absorbing the x-ray emission. Perhaps this explained why so few of the cataclysmics were being detected at x-ray wavelengths.

In May of 1978 it became apparent that the low-energy detectors of the A-2 experiment were running out of gas. So the gas supply to the detectors was shut off to conserve what little remained for one or two future "targets of opportunity." Essentially, it appeared to be the end of the HEAO-1 soft x-ray mission.

Then, two weeks later I got a telephone call from Jim Morgan, an AAVSO member who lives in Prescott, Arizona, and who had been an active participant in the Cataclysmic Variable Survey. "Your star is up!" Jim exclaimed. He had not heard about the detector shut-down. I contacted the head of the Caltech x-ray group, Professor Gordon Garmire, who is also a principal investigator on the HEAO-1 A-2 experiment. Although Professor Garmire agreed that the erupting SS Cyg was a worthwhile target for a last detector pointing, he was not optimistic about getting a pointing with such short notice. Many people at Goddard had to be contacted and given specific instructions for the delicate business of reactivating the detector. Also there was the fact that all the observing slots for the next week had already been scheduled for other experiment pointings. However, in the end, we obtained a 6 hour observing period for the following day.

The dwarf nova was already in its fifth day of outburst, and there was some uncertainty over whether or not it would stay bright through the pointing, but members of the AAVSO kept an all night vigil and assured us that the star was at peak brightness (see inset in Fig. 3). The pointing was carried out the next afternoon. We had no idea whether the gas supply would hold out for the duration of the observation, or if the very delicate (1 μm thick) detector window would still be intact after the long detector shut-down.

Two days later, through the efforts of John Aiello and others at Goddard, we had in our hands a tape containing one satellite orbit (90 minutes) of the SS Cyg pointing. We simply could not believe what we saw when we plotted the data (Fig. 3): SS Cyg had large amplitude x-ray pulsations with a period of ~8.8 seconds.

The period was not regular. First of all, it decreased slowly ($dP/dt \sim 10^{-5}$ sec sec^{-1}) throughout the observation. Secondly, there were random phase "glitches" during which the period would quickly shift by up to 100 milliseconds. And finally, the amplitude of the pulsations varied from 0 to ±50%. The changing period ruled out the previous hypothesis of a magnetic field as the cause of the oscillations (which have been observed in the optical band in many cataclysmic variables). The large amplitude of the x-ray pulsations, and their coherence, also seemed to rule out blobs of matter circulating in the inner disc. The origin of the pulsations was clearly the region close to the white dwarf surface, but no one was quite sure what kind of instabilities would produce the large amplitude, coherent x-ray pulsations.

Since the A-2 low-energy detector used for the SS Cyg observation had held up remarkably well for the pointing, we decided to go for U Gem if it had an outburst when it was fairly close to the HEAO-1 scan plane. That meant waiting until October of 1978, when there was a 3 week HEAO-1 window on U Gem. Janet Mattei marshalled many AAVSO members into keeping a constant watch on this star during October. Those of you who follow dwarf novae know that on Oct. 13, 1978, U Gem started to rise.

There was some panic in the Caltech HEAO-1 data room. The weekend was near and few HEAO-1 operators would be on duty in the control room at Goddard. Also, the outburst looked as though it would be short and not very bright (both estimates turned out to be correct), so we did not have much time to schedule a pointing. There were two choices for a pointing open to us: the night of Oct. 13, when we thought the star would reach peak visual brightness, and the night of Oct. 15 (Oct. 16 U.T.). We decided, finally, to go for the latter because (1) there was some suspicion that, based on the detection a year before (Fig. 1), the soft x-rays might be delayed, (2) SS Cyg had been observed at peak visual brightness and the x-ray oscillation period was observed to decrease; we wished to see if on the declining portion of the outburst light curve the oscillations in U Gem would increase and (3) we could have a 10-hour observation period, or 2 1/2 orbital periods of U Gem, if we waited for the second observing slot. At the start of the HEAO-1 observation -- when all systems were "go" and there was no way to halt the observation -- the variable star observers informed us that the star was at 10th magnitude and declining (see inset Fig. 4). We were afraid we had waited too long.

The first indication that luck was with us came several hours later, when we received a couple of minutes of data in real time during a satellite-to-ground station pass. It was clear from the large count-rate, far above the normal x-ray sky count rate, that U Gem was (still) a bright soft x-ray source. When we eventually received all of the data, two things were immediately apparent: (1) there was no gross modulation of the x-ray light with the orbital period of the systems and (2) half of the x-ray light was modulated with a 20-30 second "quasi-coherent" oscillation. (Fig. 4).

It had been observed, on one occasion only, that the soft x-ray light from AM Her was also modulated, with a ~38-second period for several oscillation periods, and there were other similarities between SS Cyg, U Gem, and AM Her. All showed (during some outburst phase) weak hard x-ray emission and all had intense soft x-ray fluxes. The ratio of the soft to the hard x-ray flux was about ten for all three systems, but how were the soft and the hard x-ray flux related? Was the soft x-radiation due to reprocessing of the absorbed hard x-radiation? Would all cataclysmic variables which emitted soft x-rays turn out to be x-ray pulsators? What were the timescales of the pulsations telling us about the source of the oscillations? What was the behavior of the pulsations telling us?

You may have noticed that, while I have posed many questions, I have not given any answers, only clues which are difficult to interpret. There are still many pieces of data to be analyzed before a complete scenario should be attempted. What I have tried to do here is to relate a few of the very special moments on HEAO-1, moments which many amateur astronomers shared with us. I have also tried to point out some of the problems in understanding cataclysmic variables.

The visual light curves presented here are the result of many hours of observations by variable star astronomers all over the world. The experimenters at all the HEAO-1 collaborating institutions are sincerely grateful for these data, which are appearing in

scientific publications with acknowledgements to the AAVSO and VSS (New Zealand). For myself, it was a great thrill to work with these astronomers.

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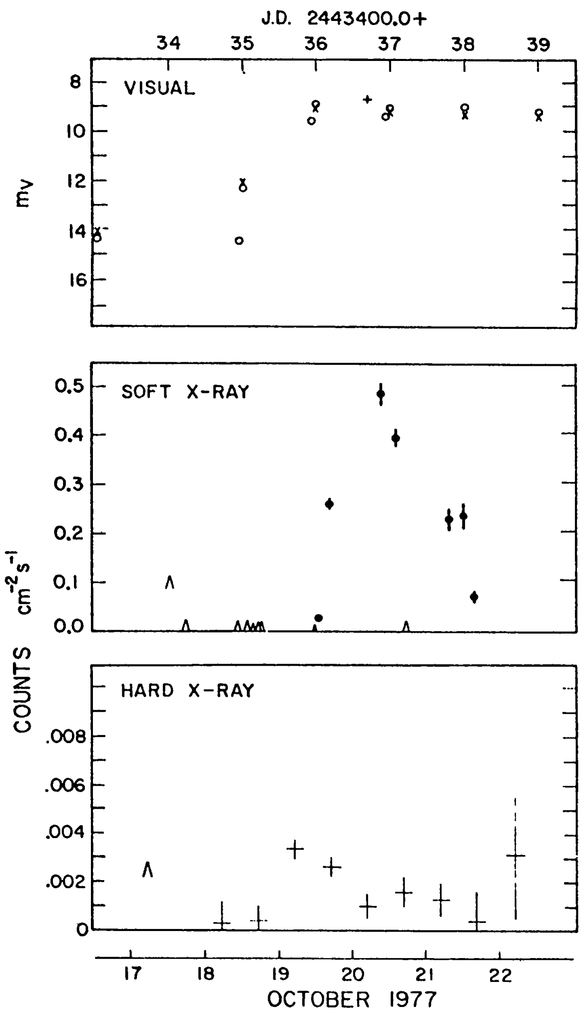

Figure 1. The first detection of x-rays from U Geminorum during an optical outburst. Illustration is similar to that appearing in Mason, Cordova and Swank (1978).

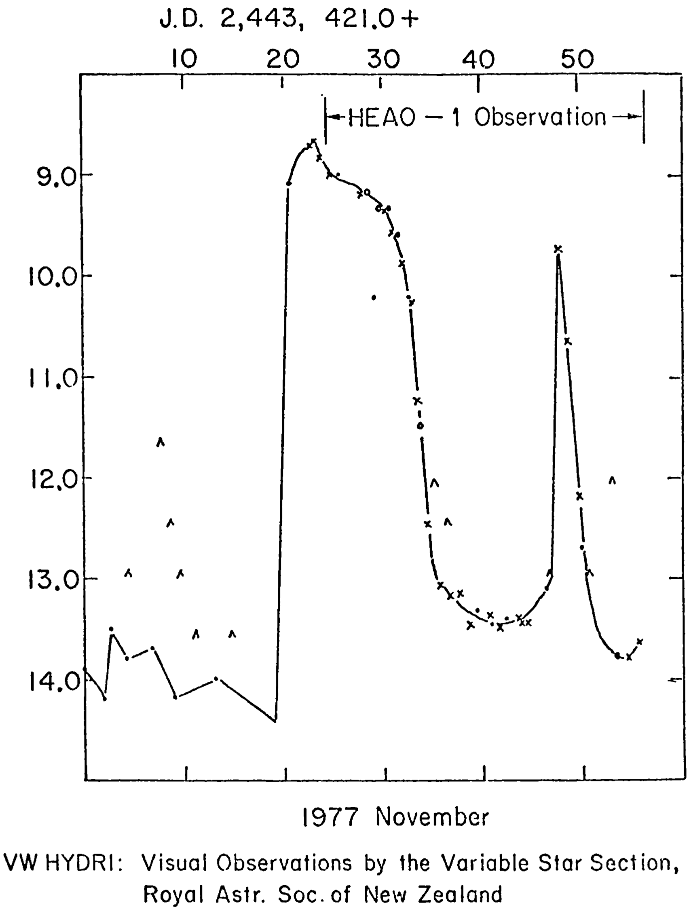

Figure 2. The light curve of VW Hydri provided by the Royal Astronomical Society of New Zealand Variable Star Section. No x-rays were detected during the ∿30 day HEAO-1 observing period.

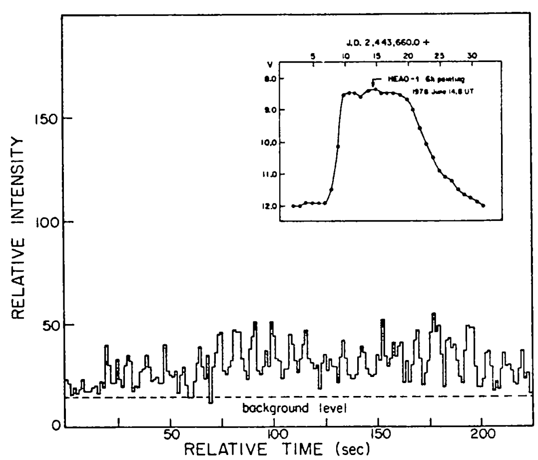

Figure 3. The soft x-ray (0.15-0.43 keV) pulsations from SS Cygni. The inset shows the AAVSO light curve for the June 1978 outburst during which 9 second pulsations were discovered.

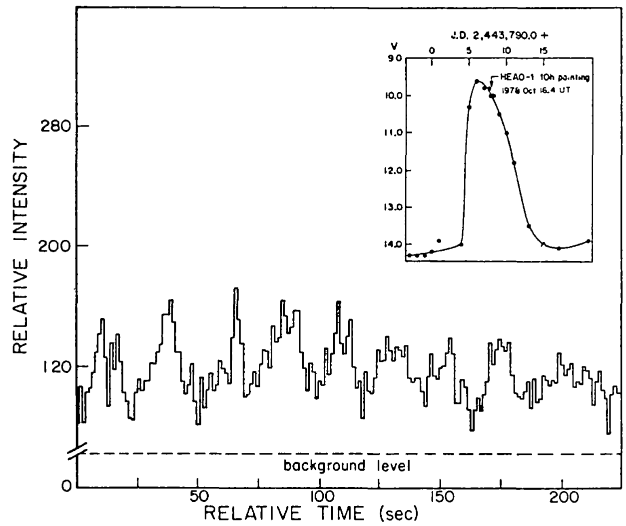

Figure 4. The quasi-periodic nature of the soft x-ray (0.12-0.20 keV) emission from U Geminorum. The inset is the AAVSO light curve for the October 1978 outburst during which ∿25 second oscillations were detected.

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