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Studies of an X-ray Selected Sample of Cataclysmic Variables

by

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ABSTRACT

Just prior to the thesis research, an all-sky survey in hard X-rays (1-20 keV) with the HEAO-1 satellite and further observations in the optical resulted in a catalog of about 700 X-ray sources with known optical counterparts (Remillard *et al.* 1992). This sample includes 43 Cataclysmic Variables (CVs), which are binaries consisting of a detached white-dwarf and a Roche lobe filling companion star. This thesis consists of studies of the X-ray selected sample of CVs.

This thesis consists of 4 parts:

1) **Classification**; Each of the newly discovered CVs is studied, with the hope of determining its membership in one of five CV subclasses: nova-like, dwarf nova, high state, DQ Her and AM Her. Periodic variations in the optical light curve of H0204-029 suggest that this system may be a DQ Her. Optical light curves helped determine orbital periods for H1752+081, H1903+690 and H0928+501. Outbursts observed on the photographic plates archived at the Harvard College Observatory allowed us to identify H0204-029, H2118-342, and H0857-242 as dwarf novae. The system 1ES1113+432 was observed to be in a bright state for a nine year period, based on the HCO plates.

2) **Class Properties**; Optically-thin accretion disk models are found to successfully model the emission line strengths, but only for those spectra in which the equivalent widths of all lines are greater than 20Å.
Statistical properties of our sample are compared to the optically selected PG sample (Ringwald pvt. comm.). There is a significantly higher percentage of magnetic systems in our sample than in the PG sample, confirming the importance of magnetic focusing in the production of hard X-ray emission. In other ways (*e.g.* the percentage of dwarf nova and the period distribution) the samples were found to be nearly identical. The number of eclipsing systems in both samples is compared to a parent population with a uniformly distributed angle of inclination; no statistically significant deviation from a uniform distribution was seen.
An upper limit can be placed on the magnetic field strength of the DQ Her systems. For some of theses systems, the upper limit is sufficiently high that some of the DQ Hers may

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A MULTI-FREQUENCY STUDY OF AN X-RAY SELECTED SAMPLE OF ACTIVE GALACTIC NUCLEI

by

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ABSTRACT

The LASS (Large Area Sky Survey) experiment, which flew aboard the HEAO-1 spacecraft, carried out a 2-20 keV survey of the sky during 1977–1978. The X-ray sources from this survey make up the LASS catalog (Wood et al. 1979). Optical counterparts have been identified for greater than 86 % of the LASS sources above a flux of ~0.95 μJy @ 5 keV (Remillard 1992b). The LASS error boxes, along with the more precise positions from the Modulation Collimator (MC) X-ray experiment (also aboard HEAO-1), subsequent X-ray imaging, and optical search techniques were all used to identify the LASS sources. From these identifications, a high-latitude ($|b| > 20°$), flux–limited (≥ 0.95 μJy) sample of 96 emission line Active Galactic Nuclei (AGN) have been selected for study. The sample is referred to as the LMA (for the LASS / MC identified sample of AGN). The objective of this work is to produce multi-frequency spectra of this sample of objects, in order to determine and interpret the statistical properties of the sample over nearly the full range of observable wavelengths.

Data were obtained for as much of the radio through hard X-ray (< 20 keV) spectrum as possible for each object in the LMA. Radio, near infra-red, and other measurements were taken from the literature, far IR fluxes were extracted from co-added observations from IRAS, UV spectra were obtained from the IUE archives, and original observations were performed (with the help of collaborators) in the radio, near IR, optical, UV, and X-ray to fulfill this goal.

Correlation studies of the continuum bands found poor correlations of X-ray and radio flux, good correlations for 12 and 25 μm flux with X-ray flux, excellent correlations for optical and near IR fluxes with X rays, and poor correlations of UV and X-ray fluxes. The correlations of fluxes in widely separated bands, along with the identification of thermal components on smaller frequency scales, suggest that AGN multi-frequency spectra are made up of an underlying component from the IR to the X-rays which is similar in most AGN, plus thermal components which vary widely from object to object. For objects without significant stellar contamination or reddening, the log slope from 1.25 μm to 5 keV has a mean of –1.04 with a standard deviation of 0.05 (~twice the typical measurement uncertainty). This result suggests that the underlying component has a small range of slopes centered near –1. In order to study the intrinsic distribution of blue bump strengths, broad-band spectral shapes and other spectral features were used to identify the presence of reddening and starlight contamination. The distribution of blue bump strength relative to the 1 μm flux, characterized by the log slope from the near IR to the UV, is found to vary significantly, with no observable dependence on luminosity. The near IR to UV log slopes from 20 objects diagnosed as un-reddened and uncontaminated by starlight range up to +0.12, and appear to approach a lower limit of –1. These results suggest that the blue-bump thermal component is superimposed on a ~ –1 log slope underlying component from 1.25 μm to the UV. In the objects with IR to UV log slopes near –1 the underlying continuum component is viewed directly because the thermal blue bump component is weak or absent.

Correlation studies of line and X-ray continuum flux yield a good correlation between the flux of [OIII], the strongest narrow emission line, and X-ray flux. The Balmer lines, however, do not show a strong correlation with X-ray flux. He I and Fe II emission in a band which includes 5200Å and 5320 Å

evolve into AM Her systems. However, for the most likely value of the white-dwarf mass, most DQ Hers will not evolve into AM Her systems.

3) **Detailed Studies of Individual Systems;**

H1752+081: This eclipsing nova-like system has high equivalent width of Hβ, purported to be a strong indicator that the accretion disk is optically thin. Through the eclipse ingress and egress, we obtained the masses of the stars ($M_1 = 0.80 \pm 0.06 M_{\odot}$ and $M_2 = 0.32 \pm 0.06 M_{\odot}$) and the radius of the accretion disk ($R_D = 0.19 \pm 0.03\ a$, where a is the separation of the two stars). The disk is faint and small, compared to other eclipsing CVs. The broad band emission originates primarily in two regions: the hot spot and a compact central component, which may be either the white-dwarf surface or the boundary layer between the accretion disk and the white-dwarf surface. The emission-line velocities do not show the "Z-wave" expected from the eclipse of a Keplerian accretion disk, nor do they have the correct phasing to originate near the white dwarf. The most likely origin of the line emission is the hot spot. Many features (*e.g.* the small accretion disk) of this system suggest a significant white-dwarf magnetic field strength. No unambiguous indicators (*e.g.* polarized light) of the white-dwarf magnetic field have been detected.

H0538+608 (BY Cam): A concurrent X-ray/optical observing program was undertaken to study the anomalous AM Her type H0538+608 (BY Cam). We found evidence that the orbital period differs from the rotational period by 1.3 ± 0.1 %. If confirmed, this would be the second AM Her system found to rotate asynchronously; this would explain much of the unusual behavior previously exhibited in optical photometry and polarimetry. The transition in the X-ray state that occurred on 1988 February 9.5 (Ishida, Silber, Ohashi, Bradt, Remillard 1991) was also evident in the behavior of the optical continuum and the Hα emission. Before the transition, the accretion occurred onto 2 spots, one of which was periodically occulted by the body of the white dwarf. After the transition, all the accretion was funnelled onto the non-eclipsing spot. On 1988 February 8.065 both spots are shown to lie in the northern hemisphere and on the side of the white dwarf opposite from the companion star. The primary characteristics of the optical and X-ray light curves and the radial velocity measures of Hα are consistent with our geometric model. An optical QPO with a period of ~ 30 min was seen on two nights and possible causes of the QPO are discussed. The short timescale variations in the X-rays and optical light were highly correlated. The X-ray–optical cross correlation is maximum at zero time lag but is clearly asymmetric in the sense that optical power lags X-ray power.
This work has already resulted in two published papers: Ishida, Silber, Bradt, Remillard, Makishima, Ohashi 1991 and Silber, Bradt, Ishida, Ohashi, Remillard, 1992. I played an central role in both papers.

4) **Theoretical Models of CV Evolution and Magnetic Interactions:** We have used a preexisting bi-polytrope code (Rappaport, Verbunt, and Joss 1983) to study the effects of different initial conditions on binary evolution. We show that CVs detected in the period gap, such as H0709-360, may be the result of a low initial mass of the secondary..I have extended the code of Rappaport *et al.*, to study the time history of the white-dwarf spin period under the effects of the accretion toque and the MHD torque of Lamb *et al.* (1983). We follow the spin rate for an ensemble of magnetic field strengths of both stars. We find that for much of parameter space, magnetic CVs are asynchronous above the gap (DQ Her) and synchronized below the gap (AM Her).

showed the best broad line correlations with X-ray flux. No significant correlation is observed between optical line flux and the UV continuum flux. However, all measured high-ionization UV line fluxes correlate very well with the simultaneously measured UV continuum. The good correlation of narrow [OIII] flux with X-ray flux is consistent with a simple picture for the narrow line region where a high-energy continuum, which is distributed over a large solid angle, and which is represented by the X-ray flux, photoionizes the gas in the narrow line region. If the UV continuum is assumed to originate in a disk, the correlation of UV line flux with the UV continuum flux, but not with the more isotropic X-ray flux, would suggest that UV line emission also originates in the disk. A very large spread in the value of broad line Balmer decrements ($H\beta/H\alpha \sim 0.13 - 0.4$) is observed among objects determined to be un-reddened ($E(B-V) \leq 0.03$) by observation of their 2175 Å feature. If there were an intrinsic Balmer decrement for broad line regions in AGN, this spread would correspond to extreme values of reddening ($E(B-V)$>1 mag), therefore the broad line Balmer decrement is not useful in determining continuum reddening in most AGN.

Repeated observations of some of the LMA objects were used to assess the effects of variability on the conclusions above. The median fractional variability was found to be 29% in the UV, and 11% in the optical. A comparison of X-ray fluxes in the literature yielded an average fractional rms variability of 39%. A survey of the literature showed that variability greater than a factor of 2 was found to be rare in all but the IUE bands; such variations are insufficient to affect the correlations in luminosity discussed above, which have spreads of 1/2 to one decade. An X-ray observation of the object 1H0557-503 (PKS0558-504), yielded significant variation on a time scale ≤ 200 s, the fastest ever observed in a normal quasar. The inferred rate of change of luminosity ($dL/dt \approx 3.2 \times 10^{42}$ erg s^{-2}) is the first strong evidence that X rays from a normal quasar may be beamed.

The hard X-ray Luminosity Function (LF) of the LMA can be roughly described by a power law of slope -2.49 ± 0.02 from $10^{42} - 10^{48}$ erg s^{-1}, but the function steepens with increasing luminosity. Below 10^{42} erg s^{-1}, the LF flattens very significantly, and is not modeled well by a power law. The low-luminosity flattening has not been previously observed in the hard X-ray band, but has been reported in the soft X-ray EMSS sample (Maccacaro et al., 1991). The flatness of the LF at low L_X and the steepness of the LF at high L_X allows a more certain estimate of the contribution of AGN to the 2–10 keV diffuse X-ray background than available previously. Integration of the LF from $L_X = 8.9 \times 10^{41}$ to 2.17×10^{47} erg s^{-1} yields a contribution to the background of 26^{+8}_{-11} %. The X-ray LF of narrow lined objects can be described by a power law at low luminosities, with a log slope of -2.32 ± 0.19 from 10^{42} to $10^{43.5}$ erg s^{-1}. Above $10^{43.5}$ erg s^{-1}, however, the LF is truncated or becomes significantly steeper. The cumulative fraction of narrow-lined objects in the LMA for $L_X > 10^{43.5}$ erg s^{-1} is much lower (<1/5) than the total fraction reported for unbiased optical, IR, or radio samples. Either there is an intrinsic dependence of narrow-line fraction on X-ray luminosity, or hard X-ray selection is biased against detecting narrow-line AGN compared to broad-line AGN at high luminosities.

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GINGA OBSERVATION OF AN AM HERCULIS TYPE SOURCE H0538+608

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ABSTRACT

Results from a *Ginga* observation of the AM Her type object, H0538+608, carried out on 1988 February 7–10, are presented. During the first half of the observation (pulsing state) the source showed periodic modulations caused by the white dwarf rotation, and the modulation profile was characterized by a flat top and a flat bottom. During the second half, the source was in a remarkable flaring state and the periodic modulation disappeared. The dramatic change of the X-ray light curve is interpreted in terms of a change of accretion pattern between an eclipsing spot and a noneclipsing spot. The phase determined by the X-ray data coincides well with that expected from the optical polarimetry data by Mason *et al.*, providing strong support for their tentative precise ephemeris.

The spectrum is well described throughout by a thin thermal model including an iron *K*-line with equivalent width of some hundred eV, supporting the standard model for the hard X-ray emission region. The temperature in the pulsing state was found to change with the spin phase of the white dwarf. In the flaring state, the temperature showed a positive correlation with the source luminosity.

Subject headings: stars: accretion — stars: individual (H0538+608) — stars: white dwarfs — X-rays: binaries

I. INTRODUCTION

The AM Her type sources are cataclysmic variables containing a late type star and a strongly magnetized ($\sim 10^7$ G) white dwarf (Cropper 1990). The dipole magnetic field of the white dwarf is so strong that the spin of the white dwarf is synchronized to the orbital motion of the binary system. The strong magnetic field controls mass flow from the optical counterpart to either one or both magnetic poles of the white dwarf, and a standing shock is formed near the surface. Below the shock, the kinetic energy of the flow is converted into thermal energy, producing strong hard X-ray emission. In general these sources are observed as "white dwarf pulsars," for the dipole axis of the white dwarf is usually tilted with respect to the spin axis.

As pointed out by Lamb (1985), there are three important emission mechanisms in AM Her type sources: (1) optical cyclotron emission originating from the accretion column; (2) optically thick UV to soft X-ray emission (with a temperature of 20–50 eV, usually approximated by blackbody radiation) from the white dwarf surface; and (3) optically thin hard X-ray emission (with a temperature of a few times 10 keV) from the postshock hot region. It is not yet clear, however, how gravitational energy of the accreting matter is distributed among these three components. For example, if blackbody emission from the white dwarf surface is reprocessed emission from the other two mechanisms, its luminosity should be of the same order as the total power of the other two from a simple geometrical consideration, namely $L_{bb} \sim L_{br} + L_{cyc}$. But observations of AM Her type sources indicate that $L_{bb} = (1\text{–}50) \times (L_{br} + L_{cyc})$ (Lamb 1985 and references therein). This is the so-called soft excess problem. For a better understanding of the emission mechanism in AM Her type sources, knowledge of the hot plasma in the postshock region is necessary. For this purpose, hard-X ray spectroscopy is essential.

The X-ray source H0538+608 was detected by *Uhuru* and the *HEAO* 1 LASS (Large Area Sky Survey) and cataloged as 4U 0541+60 (Forman *et al.* 1978) and 1H 0533+607 (Wood *et al.* 1984), respectively. The 2–10 keV X-ray flux of this source is exceeded only by two others of the same type (AM Her itself and EF Eri).

Remillard *et al.* (1986) optically identified this source as a star with $B \sim 15$. They pointed out that H0538+608 was in a low state ($B \geq 17$) in 1934 and 1939. Such a low state is a common property among cataclysmic variables. In addition, the source showed other characteristics that are common to AM Her type sources, including 10% circular polarization, strongly modulated brightness variation, and intense flickerings on time scales of seconds. They also found that the energy flux in an optical band (300–700 nm) is 2×10^{-11} ergs cm^{-2} s^{-1}, and the rotation period of the white dwarf is 3.1 ± 0.2 hr based on optical polarimetry. Recently, Mason, Liebert and Schmidt (1989) performed long-term optical polarimetry that yielded a refined rotation period of 3.331 ± 0.015 hr, despite strong aperiodic behavior.

In the UV band (Bonnet-Bidaud and Mouchet 1987), the 120–320 nm flux is 2.6×10^{-11} ergs cm^{-2} s^{-1}, and the spectrum is characterized by unusual carbon and nitrogen emission lines which are commonly seen in the spectra of old novae.

X-ray observations of H0538+608 with *EXOSAT* (Shrader *et al.* 1988) have revealed a number of remarkable characteristics. Soft X-ray eclipses, confined to X-ray energies below 1 keV, indicate the occultation of the X-ray–emitting region by an accretion stream with a period of 3.30 ± 0.03 hr. Simultaneous X-ray, UV, and optical observations indicate a notable absence of the "soft excess" which characterizes other AM Her systems. Even more striking, however, is the chaotic appearance of the X-ray light curves from the Medium Energy (ME) experiment (1–8 keV). The X-ray intensity surges were as large as a factor ~ 6, on a time scale ~ 1 hr. There were no apparent changes in the X-ray spectrum, although the ME detector could only set a lower limit on the temperature; $kT \geq 23$ keV (90% confidence limit). The unstable behavior in the X-ray and optical (Silber *et al.* 1990) light curves and in the optical polarimetry suggests the possibility of asynchronous rotation such as

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the hard X-ray spectrum. Since the energy transfer time scale is inversely proportional to the ion density, the electrons are heated up to higher temperature for higher mass accretion rate before landing on the white dwarf, in good agreement with the result shown in Figure 6*a*. But note that the discussion here needs further careful evaluation, especially concerning the efficiency of cooling mechanisms such as bremsstrahlung, electron conduction, and Compton cooling due to soft photons radiated from the white dwarf surface.

e) *Mass of the White Dwarf*

If the observed temperature, T_{obs}, is equal to the shock temperature, T_s, one can estimate the white dwarf mass using the theoretical relationship between the white dwarf mass and radius. However, there are reasons that T_s may be greater than T_{obs} (Fabian, Pringle, and Rees 1976; Kylafis and Lamb 1982; Imamura and Durisen 1983; Frank, King, and Lasota 1983):

1. The equipartition of internal energy may not be attained between ions and electrons.
2. The postshock electrons cool by thermal bremsstrahlung.
3. The thermal conduction from the shock front to the postshock region may not be negligible.
4. Compton scattering of the soft photons from the white dwarf surface may be effective.

Thus, only a lower limit to the white dwarf mass can be estimated. The highest temperature observed is 37.6 ± 3.0 keV for the flat-top phase in the pulsing state. From this,

$$M_{WD} \geq 0.71 M_\odot . \quad (1)$$

This relation is derived by assuming that the shock occurs on the surface of the white dwarf. An improved result could follow from optical spectroscopy and polarimetry (e.g., Mukai and Charles 1987).

V. CONCLUSIONS

The AM Her type source H0538+608 has been observed with *Ginga*. The results confirm that the hard X-ray spectrum can be described by thin thermal emission, supporting the existence of a standing shock. The behavior of H0538+608 changed in the middle of the observation. In the first half (pulsing state), modulation of the light curve caused by the white dwarf rotation was clearly seen, whereas in the latter half (flaring state) it disappeared.

In the pulsing state the observed temperature (~38 keV) is higher than that of the other two AM Her type sources observed in X-rays, AM Her (30 keV: Rothschild *et al.* 1981) and EF Eri (18 keV: Patterson, Williams, and Hiltner 1981). In the flaring state, the temperature of the emission region increases with the mass accretion rate.

The X-ray pulsing state appears to require two active poles because (1) the X-ray spectra indicate optically thin thermal emission, (2) the folded X-ray light curves in the pulsing state have a flat-top and a flat-bottom shape, and (3) a substantial flux remains during the flat-bottomed region. The absence of periodicity in the flaring state further argues that one accretion spot is always in view; the accretion flow is directed primarily to this noneclipsing pole during the flaring state. In this active 2-pole picture, previously put forward by Mason, Liebert, and Schmidt (1989) to explain their polarization data, the other pole is periodically eclipsed by the white dwarf. The polarization feature that represents the emergence of this eclipsing pole is in precise coincidence with the upward transition from the flat bottom to the flat top of the X-ray light curve, if their tentative, but very precise, ephemeris is adopted. This establishes with some confidence a physical connection between the X-ray and optical emission and provides support for their ephemeris.

Two cautionary notes are in order: (1) this scenario for the X-ray emission is based upon the interpretation that the folded X-ray light curve is truly flat-topped and flat-bottomed (i.e., the profile is not an artifact of the folding process); and (2) the optical spectroscopy and photometry obtained simultaneously with the X-ray data (to be published) indicate a more complex and time-dependent situation which requires additional detailed modeling.

A lower limit of the white dwarf mass is obtained by means of the maximum observed temperature. We obtain ~0.7 $M_\odot$ from the present observation.

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