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DISCOVERY OF SOFT X-RAY EMISSION FROM V471 TAURI AND UU SAGITTAE: TWO HIGHLY EVOLVED, LOW-MASS BINARIES

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ABSTRACT

We report here the discovery of soft X-ray emission from two highly evolved low-mass binaries using the *HEAO 1* A-2 experiment. V471 Tau is a 5×10^{30} ergs s^{-1} source in the Hyades with a white dwarf and K V star as components. UU Sge is a planetary nebula nucleus containing an sd0-B star and a K V-M V companion with a soft X-ray luminosity of $\sim 10^{32}$ ergs s^{-1}.
Subject headings: stars: binaries — X-rays: sources

I. INTRODUCTION

The discovery of RS CVn stars as soft X-ray sources (Walter, Charles, and Bowyer 1978) suggests that one criterion for a star to show strong coronal X-ray emission is that it must possess a convective envelope in rapid rotation for its spectral type. Late-type stars have outer convection zones resulting from high opacity in the region where hydrogen becomes ionized, but these stars are generally slow rotators (Tassoul 1978). Because of the slow rotation associated even with the Keplerian velocity at the surface of late-type giants, we may exclude them from consideration as rapid rotators. Luminosity class IV or V stars of late type are thus indicated as potential X-ray emitters provided they are in rapid rotation, for example, those which are members of short-period binaries and are more or less locked tidally into synchronism (see Zahn 1977 for a discussion of the synchronization mechanism). Several classes of stars which satisfy the above criterion are:

1. The RS CVn stars: A growing list of RS CVn stars shows soft X-ray emission (Walter, Charles, and Bowyer 1980) which is attributed to coronal activity associated with the subgiant component.
2. Contact binaries of late type: There are 71 contact binaries of type later than F5 listed in the *General Catalog of Variable Stars* and its supplements (Kukarkin *et al.* 1969, ff.). These objects, as we will show in § II, do not seem to be copious emitters of soft X-radiation (0.18–2.5 keV).
3. Late main-sequence stars with a close ($P \leq 1$ day), compact companion: In this class there are only three objects in the literature, namely V471 Tauri (=BD +61°516, Nelson and Young 1970), PG 1413+01 (Green, Richstone, and Schmidt 1978), and UU Sagittae (Bond, Liller, and Mannery 1978). These binaries typically consist of a white dwarf or a subdwarf in an 8–13 hr orbit about a main-sequence K or M star. In this *Letter* we show that V471 Tau and UU Sge are soft X-ray sources.

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II. OBSERVATIONS

In order to search for soft X-ray emission from the contact binaries of late type or the evolved, low-mass, close binaries, we have examined data from the Low-Energy Detectors (LEDs) of the A-2[2] experiment on board the *HEAO 1* satellite. We have used data from LED 1, which is a gas proportional counter with a sensitivity range from 0.1 to 3.0 keV (see Rothschild *et al.* 1979 for a detailed description). A survey of almost the entire sky was performed with this instrument; for maximum sensitivity to point sources, we utilized the $1\frac{1}{2}° \times 3°$ field of view.

We have developed an automatic search procedure which correlates the detector collimator response function with the data in order to flag potential sources. This list of potential sources was then checked against the lists of late-type contact binaries and evolved eclipsing binaries of low mass. Positional coincidences were then more closely examined to test whether the flagged feature was consistent with a point source at the star's position at a significance greater than 3 σ. None of the contact binaries survived this test, although three, VW Boo, UX Eri, and VZ Lib fall near new flagged sources which were subsequently found to be spurious. On the basis of previous experience (Walter *et al.* 1980), we would have expected approximately two sources at $>3\ \sigma$ from 71 random positions. We can set an upper limit to the 0.18–2.5 keV X-ray flux of these objects as a class of about 10^{-11} ergs cm^{-2} s^{-1}.

The evolved low-mass close binaries. In the search of the A-2 experiment data we found weak sources at the positions of two of these objects: H0349+17 coincides with V471 Tau and H1938+16 with UU Sge as seen in Figure 1. These are 90% confidence-level error boxes determined using the triangular response of the collimator to a weak source. We estimate a probability of 3×10^{-4} that two out of three of these objects will fall within the *HEAO 1* A-2 error boxes if these stars represent random positions on the sky.

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

The source H0349+17 (see Table 1) is a 4.2 σ detection of an incident 0.18–2.5 keV band flux of $2.4 \pm 0.7 \times 10^{-11}$ ergs cm^{-2} s^{-1}. A fit to a simple thermal bremsstrahlung spectrum gives a temperature $\log T = 6.7 \pm 0.3$. Associating this source with V471 Tau at a distance of 42 pc (Young and Capps 1971) implies a 0.18–2.5 keV band luminosity $L_x = 5 \times 10^{30}$ ergs s^{-1}.

H1938+16 (see Table 1) is a 4.5 σ source with a flux of $3.0 \pm 0.8 \times 10^{-11}$ ergs cm^{-2} s^{-1} in the same energy band. We have fitted this spectrum to a thermal bremsstrahlung model attenuated by Brown and Gould interstellar absorption (Brown and Gould 1970). This fit yields a $\log T = 6.5 \pm 0.2$ and a column density $\log N_x = 21.0 \pm 0.3$. The use of a Raymond and Smith (1977) coronal plasma model does not significantly change either T or N_x from these values. Using Fitzgerald's (1968) values of the color excess at various distances in this direction and Spitzer's (1978) relation between the color excess and the hydrogen column density, the mean hydrogen number density $n_{\rm H}$ is found to be 1 cm^{-3} out to 1.5 kpc along this line of sight. Thus the X-ray column density N_x implies a distance to the source of 300 pc and $L_x = 10^{32}$ ergs s^{-1}. The formal errors in these quantities are a factor of 2 and 4, respectively.

No source appeared at the position of PG 1413+01 although there is a weak new source, H1423+01 within $\sim 2°$. We can set an upper limit to the 0.18–2.5 keV band flux of 1×10^{-11} ergs cm^{-2} s^{-1}, comparable to the upper limit for the contact binaries.

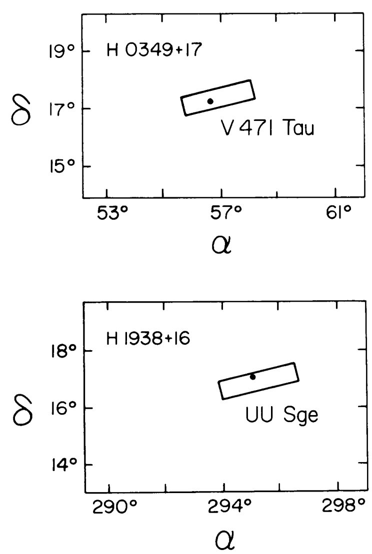

FIG. 1.—90% confidence-level error boxes

TABLE 1

SOURCE CHARACTERISTICS

Parameter	H0349+17	H1938+16
Detection	4.2	4.5
Flux (ergs cm^{-2} s^{-1})	2×10^{-11}	3×10^{-11}
Temperature (simple bremsstrahlung spectrum)	$\sim10^7$ K	$\sim5\times10^6$ K

III. DISCUSSION

It is not uncommon for contact binaries of late type to show light curve variations from epoch to epoch similar to the photometric waves seen in RS CVn stars, for example, VW Cep and AH Vir (Kukarkin *et al.* 1969). These waves are widely interpreted as evidence for starspots and, hence, solar-type activity including active chromospheres and coronae. An upper limit to the X-ray luminosity of these objects as a class can be found by considering the nearest such object, 44 ι Boo. Hoffleit (1964) lists a parallax of 0".076, giving a distance of 13 pc. Since it was not detected to a level of 10^{-11} ergs cm^{-2} s^{-1}, we can set this upper limit at 2×10^{30} ergs s^{-1} in this energy range.

All three of the evolved low-mass binaries show eclipses, and so their physical properties have been determined. These we summarize in Table 2. V471 Tau has been well studied (Nelson and Young 1970; Young and Nelson 1972; Young, Nelson, and Mielbrecht 1972; Young and Lanning 1975; Young 1976). The light curve has been solved, and as early as 1954 the spectrum of this star was known to show calcium H and K in emission (Bidelman 1954). More recently Guinan and Sion (1980) have obtained *IUE* spectra showing magnesium *h* and *k* also in emission. Studies by Oswalt show a strong dependence of the Ca H and K flux on orbital phase (and by presumption also rotational phase), and he indicates the similarities between this star and the RS CVn binaries (Oswalt 1979). Recently Beavers, Oesper, and Pierce (1979) have reported *U*-band flares from this system. V471 Tau has been shown to be a member of the Hyades cluster (Wilson 1953; Nelson and Young 1970) with a distance of 42 pc and an inferred age of about 5×10^8 yr.

We consider V471 Tau very likely to be the optical counterpart of the soft X-ray source H0349+17 on the basis of its position, luminosity, and similarities with the RS CVn stars.

PG 1413+01 was found by Green, Richstone, and Schmidt (1978) while conducting a search for bright quasars at the Hale Observatories. These authors derived the physical characteristics of the system using an iterative technique involving the mass-radius relation for white dwarfs and low-mass main-sequence stars. The high bolometric luminosity of this system of at least 10^{35} ergs s^{-1} is taken as an indication that its age is not much more than 10^6 yr, since this is the cooling time for a white dwarf of this luminosity (Green *et al.*). We did not detect any soft X-rays from this object. This yields upper limits on its 0.18–2.5 keV luminosity of 4×10^{30} ergs s^{-1} and 2×10^{32} ergs s^{-1} for distances of 60 pc and 400 pc, respectively.

UU Sge was only recently demonstrated to be an eclipsing binary system (Bond, Liller, and Mannery 1978), although it was originally suggested as such by Hoffleit (1932) and suspected of variability by Abell

TABLE 2

PHYSICAL PROPERTIES OF BINARIES

Parameter		V471 Tauri	PG 1413+01	UU Sagittae
m_v		10	13	15
d (pc)		40	60–400	150–2000
Cool star	spectrum	dK2	dM3±3	dM-K
	mass ($M_\odot$)	0.7	0.7±0.014	0.7
	radius ($R_\odot$)	0.8	0.7±0.014	0.7
Hot star	T_{eff} (K)	32,000	50,000	14,000–60,000[a]
	mass ($M_\odot$)	0.7	0.7±0.3	0.9
	radius ($R_\odot$)	0.01	0.01±0.005	0.4
Separation ($R_\odot$)		1.5	2.0±0.2	3
Total mass ($M_\odot$)		1.5	2.5±0.5	1.6
Period (hr)		12.51	8.02	11.16

[a] The upper limit is from Abell's Zanstra argument (see text). The lower limit is from a fit to the colors, including reddening.

(1966). Photometric studies of this star are hampered by the presence of a star only 4″ away with a brightness intermediate between the maximum and minimum light of UU Sge. The faintness and rapidity of eclipse ingress and egress also conspire to make it difficult to perform sequential multicolor photometry on this star, so only a B light curve is available. UU Sge is the central star of the planetary nebula Abell 63 (Bond 1976). In Table 2 the upper limits to the distance and effective temperature of the subdwarf are taken from Abell's estimate (Abell 1966) based on a comparison of the star's colors to the Hα flux of the nebula. We chose the lower limits by fitting the star's colors to a reddened blackbody with the photospheric temperature and extinction (n = 1 cm^{-3}) as free parameters. This gives a lower limit because the colors for the system are those for the combined light of UU Sge and the nearby star.

UU Sge coincides on the sky with the object 3C 400.2 which, as a supernova remnant, is a member of a class of known soft X-ray emitting objects. However, the distance to 3C 400.2 is greater than 5 kpc (Milne 1970), and over these distances in the galactic plane the interstellar medium is quite opaque to 1 keV radiation ($\tau \approx 5$ for $n_H \approx 1$ cm^{-3}); so we consider UU Sge the more likely candidate for identification with H1938+16.

The argument presented in the introduction (§ I) would imply that the observed X-rays originate in the corona of the late-type star. The presence of the highly evolved components in these systems makes several other competing theories for the X-ray emission eligible. These are:

1. X-rays from accretion of a wind onto the compact star (Mewe *et al.* 1975): In the case of V471 Tau this would require an accretion rate of 1.5×10^{-13} $M_\odot$ yr^{-1} onto the white dwarf. Unless the wind velocity V_W is very large (>500 km s^{-1}), the accretion radius GM_{WD}/V_W^2 is comparable to the size of the system, and a good fraction of the wind is accreted onto the white dwarf. Since the mass-loss rate required is within permissible bounds, this mechanism could account for the X-ray emission. The corresponding accretion rate for UU Sge is 3×10^{-10} $M_\odot$ yr^{-1}, implying an even larger mass-loss rate for the unevolved star.

2. Thermal X-rays from a hot photosphere on the white dwarf or subdwarf: Shipman (1976) has calculated several models with parameters similar to V471 Tau to investigate this possibility for the X-rays seen from Sirius B. He finds that for an effective temperature of 33,500 K and log g = 8.65, the expected flux in this energy range is 10^{28} ergs s^{-1}. This is several orders of magnitude less than the observed luminosity of V471 Tau; the situation is even worse for UU Sge where 10^{32} ergs s^{-1} is needed. Hence this theory would not seem to be able to explain the X-rays seen from these systems.

Since one of the U-band flares reported by Beavers, Oesper, and Pierce (1979) was seen while the white dwarf component of V471 Tau was eclipsed, a strong case can be made for the association of the soft X-ray emission with the main-sequence component. In fact, it is in principle possible to determine the site of the X-ray emission directly by examining the X-ray light curve using the *Einstein* satellite. These observations are currently in progress.

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