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Coronal X Rays from Single, Magnetic White Dwarfs: A Search and Probable Detection

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ABSTRACT. We have searched for X-ray emission from a sample of five nearby (6–20 pc), strongly magnetic (10–200 MG), relatively cool (6000–14000 K), single white dwarfs, two of which may possess coronae. We detect one star (GR 290) at better than 99% confidence and give upper limits from *Einstein* Observatory IPC data for four others. The detected luminosities and limits are in the range $1.4\text{--}12.5 \times 10^{27}$ ergs s^{-1} .

1. INTRODUCTION

Cataclysmic variables (CVs), which are binary systems containing a white dwarf accreting matter from a companion, have characteristic X-ray luminosities of $10^{29}\text{--}10^{32}$ ergs s^{-1} . The emission mechanism is thought to be thermal bremsstrahlung from coronae with temperatures of 1–10 keV and densities of $10^{15}\text{--}10^{16}$ cm^{-3} , fed continuously by the accretion stream. At least some of the heating is probably in the form of an accretion shock. These X-ray sources include many polar (AM Her) and intermediate polar (DQ Her) systems, in which the white dwarf has a strong magnetic field, as suggested by the synchronization of rotation and orbital periods and sometimes confirmed by cyclotron features and polarization in their visible and near-infrared spectra. Although these magnetic systems make up only 20% of CVs, they constitute well over half of the detected X-ray emitters (Cordova and Mason 1983; Watson 1986; Osborne 1988; Wickramasinghe and Meggitt 1985; Ferrario et al. 1989).

Up to now cool, single white dwarfs have not been detected at X-ray wavelengths. Any X rays produced in these cases would have to come from a corona. Coronae dense enough to emit detectable X rays should also produce cyclotron emission, absorption, or polarization (Zheleznyakov 1983; Zheleznyakov and Litvinchuk 1985; Serber 1990). In practice, however, these features are not always easily recognized even in systems known on other grounds to have magnetic coronae (Bailey et al. 1988). We therefore decided to search the X-ray data bases for evidence of X-ray emission from single magnetic white dwarfs.

2. THE DATA

McCook and Sion (1987) have compiled a catalog of white dwarfs and their properties and Schmidt (1989), one specifically of magnetic white dwarfs. These catalogs (augmented by data reported by Foltz et al. 1989, Saffer et al. 1989, and Ruiz and Maza 1989) yielded a sample of eight nearby, strongly magnetic, cool, single white dwarfs. Another 18 are more than 25 pc away and have relatively weak fields or are sufficiently hot that any detected X-rays might be photospheric (or both).

We examined the literature and the *Einstein* Observatory and *EXOSAT* pointing lists for the positions of our eight white dwarfs. *Einstein* Observatory IPC observations were found for five stars. *EXOSAT* observations were also found for three of these five stars observed by the *Einstein* Observatory. G 99-37 and G 240-72 have upper limits from the *Einstein* Observatory in Vaiana et al. (1981) and the latter also has an upper limit from the *EXOSAT* LE with Lexan 3000 and Al/P filters in Paerels and Heise (1989).

For two of our stars, there is some optical evidence for a corona. The spectrum of GD 356 is dominated by the usual Balmer lines of hydrogen, but in emission. That of G 240-70, on the other hand, is nearly featureless, but has a broad depression below the best-fitting blackbody continuum, from about 4400 to 6300 Å (Liebert 1976). If this is coronal cyclotron absorption (Zheleznyakov and Litvinchuk 1985), then the implied field range is 170–240 MG, consistent with other estimates. Unpublished work by Greenstein (1991) indicates that this broad feature and sharper ones in the far red can be fit by Zeeman-split Balmer lines from a surface with a complex field pattern

TABLE 1
X-Ray Results and Coronal Densities

Star	Sequence	Source ^a	Back ^b	Rate ^c	Flux ^d	Luminosity ^e	Density ^f
G 99-37	871	16	30	<6.1	<2.7	<3.7	<2.2
G 99-47	873	33	16	9.8	5.3	4.1	2.4
GD 356	8351	22	30	<5.0	<2.7	<1.3	<4.2
G 240-72	889	12	19	<6.0	<3.2	<1.4	<1.4
Grw+70°8297	893	132	197	<4.9	<2.6	<6.4	<3.0

^aIPC counts within a 3 arcmin radius.

^bIPC counts within an annulus from 5 to 6 arcmin radius.

^cNet 10^{-3} IPC counts s^{-1} .

^d0.2–3.5 keV flux in 10^{-13} ergs $cm^{-2} s^{-1}$.

^eCoronal luminosity in 10^{27} ergs s^{-1} .

^fCoronal density in $10^{12} cm^{-3}$.

and intensity ranging over 30–300 MG. GC 229, whose spectrum remains uninterpreted, is perhaps the best candidate for cyclotron features (Greenstein 1991). Unfortunately, it was not observed by the *Einstein* Observatory or *EXOSAT*.

For our targets the IPC observations are more sensitive than those performed using *EXOSAT* so we have analyzed the former. Observations were acquired from the *Einstein* Observatory databank. An X-ray signal was searched for by the standard method—a circle was defined about the source position and counts within it were accumulated and then an annulus around the circle was used to determine the local background rate. Because these observations were short and the sources are weak we must use an estimator for the source count rate that is valid for small numbers of counts. Laredo (1990) has recently developed such a method using Bayesian methods. If the number of source counts is s , the counts in the central circle n and its area a , the counts in the background annulus n_b and its area a_b , then the probability density function for s is given by

$$p(s) = \sum_{i=1}^n C_i \frac{a(s)^{i-1} e^{-s}}{(i-1)!},$$

where

$$C_i = \frac{(1+a_b/a)^i [(n+n_b-i-1)!/(n-i)!]}{\sum_{j=1}^n (1+a_b/a)^j [(n+n_b-j-1)!/(n-j)!]}.$$

We can now define the 99% confidence range of s as being between those values of s for which $P(s)=0.005$ and $P(s)=0.995$, where $P(s)$ is the integral probability distribution, $P(s)=\int^s p(x)dx$. Using this criterion the star GR 290 (=G 99-47) is detected with a 99% confidence range on the number of net source counts of 5–36. The other four stars have lower limits on their 99% confidence ranges of zero so we define their 99% upper limits as the value of s such that $P(s)=0.99$. Table 1 lists source and background counts and the derived net count rates and limits.

3. RESULTS AND DISCUSSION

The conversion factor from *Einstein* Observatory IPC counts to X-ray flux depends somewhat on (a) the intervening interstellar column, (b) the temperature of the emitting gas (assuming bremsstrahlung emission), and (c) the composition of the gas (due to lines of incompletely ionized heavy elements), though the range is only about a factor of 2 either way for $N_H=10^{19} cm^{-2}$, $kT=0.2-4.5$

keV, and $(He+metals)/H < \text{Solar}$, as appropriate for these DA white dwarfs. We have assumed here that all the stars are in the local region of the interstellar medium with $n_H \approx 0.1 cm^{-3}$ and so have N_H less than $5 \times 10^{18} cm^{-2}$, that an appropriate coronal temperature is $kT=1$ keV [1.16×10^7 K (Zheleznyakov and Litvinchuk 1985)], and that the hypothetical coronal gas is essentially pure hydrogen. The conversion factor is then about 1.85×10^{10} . That is, a count rate of $1.85 \times 10^{-3} s^{-1}$ corresponds to a flux of 10^{-13} ergs $cm^{-2} s^{-1}$ over the 0.2–3.5 keV bandwidth; and the flux from GR 290 is 5.3×10^{-13} ergs $cm^{-2} s^{-1}$.

Table 1 shows the count rate or limits and the corresponding X-ray fluxes, luminosities, and coronal densities that follow from them for the five stars of Table 2. The coronal extent is assumed to be the scale height

$$H = \frac{2kT}{GM_* m_p / R_*^2}$$

at the temperature $kT=1$ keV, for a white dwarf of $0.7M_\odot$ and $\log g=8$ $cm s^{-2}$. Such a corona will have a magnetic field energy density greatly in excess of thermal kinetic (or gravitational potential) energy density for any reasonable gas density and the magnetic fields of Table 2. The emission is assumed to be thermal bremsstrahlung from pure hydrogen gas at 1 keV, so that the Gaunt factor is roughly unity and about 80% of the total flux falls within the 0.2–3.5 keV *Einstein* band. The implied coronal luminosity and density for GR 290 are 4.1×10^{27} ergs s^{-1} and 2.4×10^{12} electrons cm^{-3} .

TABLE 2
Nearby Cool Magnetic White Dwarf Sample

Star	R.A. (1950)	Distance (pc)	Spectral Features
Alternate Name	Dec. (1950)	Field (MG)	Effective Temperature
G 99-37	05 48 46	10.6	H absorption
	–00 11.2	10	12000 K
G 99-47	05 53 47	8.0	H absorption
GR 190	+05 22.0	25	5700 K
GD 356	16 39 49	20.0	H emission
	+53 46.9	15	7500 K
G 240-72	17 48 58	6.1	Broad absorption?
GR 372	+70 52.7	200	7500 K
Grw+70°8297	19 00 40	14.3	H absorption
EG 129	+70 35.2	320	14000 K

It might be argued that we should not have expected to see anything given (a) the tighter limits on coronal density ($< 2 \times 10^{11} \text{ cm}^{-3}$) that, in principle, come from the absence of cyclotron emission features and (b) the much shorter cooling time for the coronal plasma by cyclotron emission than by bremsstrahlung. On the other hand, both points also apply somewhat to binary magnetic dwarfs that do emit X rays—the cyclotron features are not always easily discerned (Wickramasinghe and Meggitt 1985), and the ratio of cyclotron optical/IR continuum luminosity to X-ray luminosity is $< 10^{2-3}$, not the ratio of the electron lifetimes against the two processes (about 10^5). Finally, GD 356 and G 240-72 perhaps show optical evidence for coronal gas.

Independent of these arguments, one white dwarf, GR 290, has yielded a count rate significantly above the expected background rate. Although the statistical significance is strong, it is well known in astronomy that systematic errors are always underestimated so we recommend caution about this detection. In addition, there is a possibility of chance alignment with an unrelated background source. Both extragalactic and galactic confusing sources are possible, although there are no catalogued variable stars or quasars (etc.) within $5'$ of the position.

Greenstein (1991) has examined the field as shown in the Giclas (1961) catalogue and the LHS Atlas (Luyten and Albers 1979) and finds no conspicuous galaxy or nebula. There are a handful of stars within a few arcminutes but none brighter than about 13th mag. An unrelated source must, therefore, have a ratio of X ray to optical luminosity greater than 2.4×10^{-3} . The most probable candidates are a compact extragalactic source, a galactic X-ray binary (including cataclysmic variables), or a chromospherically active star. The probability of a chance superposition with an extragalactic source (most of them are AGNs) can be calculated from the Einstein Medium Sensitivity Survey. According to Gioia et al. (1990), there are 0.4 extragalactic sources per square degree to a limiting flux of $5 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$. The probability of finding one within $2'$ of GR 290 is thus 0.0014. The approximate galactic coordinates of GR 290 are $b = 204^\circ$, $l = -10^\circ$. We estimate the surface density of X-ray luminous single and binary stars capable of yielding fluxes above $5 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$ in that part of the sky to be somewhat less than one per square degree for each type. Thus the total probability of a chance background source within $2'$ (3.5×10^{-3} square degrees) of GR 290 is slightly less than 1%. IPC positions are usually better than this so our estimate is (deliberately) conservative.

Under the circumstances, we are not certain that the existence of hot coronae around single magnetic white dwarfs has been demonstrated, so higher-sensitivity observations are called for. *ROSAT* pointed observations should be able to confirm (or refute) the detection and lower the X-ray flux limits by nearly an order of magnitude from those given here, or, of course, detect the X rays.

4. CONCLUSIONS

A search of the *Einstein* data base for five nearby, single, cool, magnetic white dwarfs has yielded a probable

detection of GR 290 (G 99-47=LHS 212) and set limits for four others. The detection has 20 counts above background (99% confidence region 5–36), corresponding to an X-ray flux of $5.3 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$ and an X-ray luminosity of $4 \times 10^{27} \text{ ergs s}^{-1}$ at the parallax distance of the star. This X-ray source has a 1% probability of being a background object. The limits found for the other stars (Table 1) imply X-ray luminosities of not more than $4\text{--}14 \times 10^{27} \text{ ergs s}^{-1}$ and coronal densities less than $1\text{--}4 \times 10^{12} \text{ cm}^{-3}$.

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