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THERMAL X-RAY EMISSION FROM CLASSICAL NOVAE IN OPTICAL DECLINE

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ABSTRACT

Observations of soft X-rays emitted by the hot stellar remnant of classical nova outbursts provide a means of probing the late stage of the evolution of the remnant. Determination of the rate of evolution of the remnant may discriminate between theoretical ideas of how mass is lost from the nova envelope during optical decline and provide an estimate of the white dwarf mass that is independent of the distance. As a step in this direction, we present in this *Letter* model atmosphere calculations of the X-ray emission from the photospheres of hot, high-gravity stars, which can be used to interpret forthcoming *ROSAT* data.

Subject headings: stars: atmospheres — stars: novae — stars: white dwarfs — stars: X-rays — X-rays: sources

1. INTRODUCTION

Multiwavelength observations have revealed that a constant bolometric luminosity phase is a common feature of classical novae after optical decline. The recognition that this behavior is characteristic of all classical novae followed upon a combination of ultraviolet and infrared observations of Nova FH Serpentis 1970 (Hyland & Neugebauer 1970; Geisel, Kleinmann, & Low 1970; Gallagher & Code 1974; Gallagher & Starrfield 1976). For this moderately fast nova, the visual luminosity fell quite rapidly, with the dominance of the UV luminosity after the first week reflecting the rapidly increasing photospheric temperature. The fall in the UV after ~60–80 days and the simultaneous emergence of the infrared is due to absorption and re-emission by dust grains in the ejecta. The subsequent nondetection of FH Ser in the UV by Gallagher & Holm (1974) can be intepreted as a hardening of the spectra to wavelengths shorter than 912 Å. The detection of soft X-rays from three classical novae, Nova GQ Muscae 1983, Nova PW Vulpeculae 1984, and Nova QU Vulpeculae 1984, at times ranging from 100 to 1000 days after optical maximum with the *EXOSAT* satellite (Ögelman, Beuermann, & Krautter 1984; Ögelman, Krautter, & Beuermann 1987, hereafter OKB) has provided observational verification that the constant bolometric luminosity phase does extend to higher effective temperatures ($>2 \times 10^5$ K), as suggested by MacDonald, Fujimoto, & Truran (1985) in the context of the thermonuclear runaway model for classical novae.

The successful launch of the *ROSAT* satellite provides an excellent opportunity to explore this phase of nova evolution in detail and gives the possibility of answering some important questions regarding the properties of the stellar remnant. For example, as pointed out by MacDonald et al. (1985), the maximum temperature of the stellar remnant is dependent on the mass of the white dwarf. Hence determination of the maximum temperature gives a distance-independent estimate of the white dwarf mass, a quantity that is poorly known for classical novae. Determination of the effective temperature of the remnant as a function of time gives valuable information regarding the rate of evolution of the remnant and may help discriminate between models for the evolution of the envelope mass.

As a step in this direction, we present results of the first detailed model atmosphere calculations for the predicted X-ray flux from hot, high-gravity stars near the Eddington limit in hydrostatic equilibrium. The models are used to find count rates for the *EXOSAT* and *ROSAT* telescopes. We explore the effects of abundances differences and compare the model atmosphere results with blackbody count rates. It is also expected that the model atmosphere fluxes will be useful for detailed photoionization models of classical nova nebulae.

In the next section, we briefly review the evidence for the photospheric origin of the X-ray emission. In § 3, we present the main result of this investigation, the count rates from the model atmospheres. In §§ 4 and 5, we discuss the *EXOSAT* observations and what can be gained from the forthcoming *ROSAT* observations, respectively.

2. ARE THE X-RAYS PHOTOSPHERIC?

Since the majority of the *EXOSAT* observations were made with only the thin Lexan filter on the low-energy telescope, there is, in general, insufficient data in the X-ray measurements alone to discriminate between emission from a hot photosphere and emission from shocked circumstellar gas. OKB also find that the single observation of Nova Vulpeculae 1984 No. 2 with the Boron filter, 307 days after optical maximum, is not significant enough to exclude or support a thermal bremsstrahlung spectrum. However, they favor emission from a hot photosphere on the basis of consideration of plasma cooling times and the absence of coronal [Fe XIV] λ5303 lines that should be emitted from shocked gas (Kurtz, Vanden Bout, & Angel 1972). Krautter & Williams (1989) rule out shocked circumstellar gas by considering the degree and temporal evolution of the ionization of the ejecta of GQ Muscae and argue that it is consistent with photoionization from a hot radiation source.

EXOSAT observations made 2 months after the 1985 January outburst of the recurrent nova RS Ophiuchi (Mason et al. 1987) have been interpreted as due to X-rays from a shock front moving into a circumstellar envelope formed by the pre-outburst wind of the red giant companion (O'Brien, Kahn, & Bode 1987). Even so, the X-ray emission 200 days after outburst is consistent with an origin on the surface of a white dwarf (Mason et al. 1987).

On the basis of the otical light curve and the presence of strong He II λ468.6 nm emission, Diaz & Steiner (1989) have recently suggested that GQ Muscae is an AM Herculis variable. We can rule out accretion onto the magnetic poles of the white dwarf in such systems as the source of soft X-ray emission from classical novae by comparing the X-ray luminosity with the *EXOSAT* observations of confirmed AM Her stars (Osborne et al. 1988; Mukai et al. 1985; Beuermann 1987). Also the nondetection of EXO 033319−2554.2 (Osborne et al. 1988) through the Boron filter indicates that the X-ray spectrum of QU Vul 1984 on day 307 is significantly harder than that of AM Her stars.

3. THE STELLAR ATMOSPHERE MODELS

3.1. *Photospheric Parameters*

Observationally there are few reliable mass estimates for the white dwarfs in classical nova systems. By using empirical relations between observable quantities and underlying physical parameters of cataclysmic binaries, Webbink (1990) has obtained mass estimates for the white dwarfs in eight classical novae. The mean mass is 0.91 $M_\odot$ with an uncertainty of 0.06 $M_\odot$. To successfully model the outburst characteristics of classical novae, thermonuclear runaway theory requires that the white dwarfs in classical nova systems are significantly more massive than single white dwarfs (Truran & Livio 1989 and references therein). By relating the energetics of the outburst to the observed properties of the ejecta, MacDonald (1983) found for a sample of nine novae, that the white dwarf mass ranged from 1.0 to 1.2 $M_\odot$. More recently, by considering the expected relative frequencies of occurrence of white dwarf masses in observed classical nova systems, Truran & Livio (1986) concluded that the average white dwarf mass is $\sim$1.1–1.2 $M_\odot$. In the following, we take $M_{\rm WD} = 1.2\ M_\odot$. As argued by Truran (1979), the luminosity of the constant bolometric luminosity phase is then $L = 4.2 \times 10^4\ L_\odot$, in agreement with the luminosity–core mass relation for AGB stars and central stars of planetary nebulae (Uus 1970; Paczyński 1970). For an effective temperature, T_e, the radius and surface gravity of the remnant are

$$R = 4.75 \times 10^{10}\left(\frac{10^5\ \mathrm{K}}{T_e}\right)^2\ \mathrm{cm}\ , \qquad (1)$$

$$g = 7.06 \times 10^4\left(\frac{T_e}{10^5\ \mathrm{K}}\right)^4\ \mathrm{cm\ s^{-2}}\ . \qquad (2)$$

We have calculated stellar atmosphere models for T_e in the range 10^5–10^6 K (the corresponding log g values range from 4.85 to 8.85). The analysis of nebular emission lines show that the ejecta of novae are greatly enhanced in CNO nuclei compared to the Sun. In addition many, but not all, novae show significant enhancements of Ne, Mg, and heavier elements. These abundances are generally interpreted as indicating mixing between white dwarf core material and material accreted from the companion, with the presence or absence of substantial amounts of Ne and Mg reflecting an ONeMg or CO core, respectively. In this investigation we use two representative compositions. A " CO white dwarf" composition, based on the analyses of V1500 Cygni 1975 (Ferland & Shields 1978) and V1668 Cygni 1978 (Stickland et al. 1981) and an " ONeMg white dwarf " composition, based on the analyses of V693 CrA 1981 (Williams et al. 1985) and V1370 Aquilae 1982 (Snijders et al. 1984). Our representative abundances are given as mass fractions in Table 1. We note that GQ Muscae (Pacheco & Codina 1985; Krautter & Williams 1988; Hassell et al. 1990) and PW Vul (Kenyon & Wade 1986; Starrfield et al. 1989a; Hassell et al. 1990) fall in the first category and QU Vul (Starrfield et al. 1988b; Greenhouse et al. 1988) falls in the second category.

3.2. *Stellar Atmosphere Code*

The code used has been developed for LTE modeling of the atmospheres of hot white dwarfs and is based on that described by Mihalas, Auer, & Heasley (1975). It uses a complete linearization method coupled to a Feautrier elimination scheme. This powerful method allows successful convergence of model atmospheres very close to the Eddington limit, as are needed in the present investigation. In addition to free-free and electron scattering opacity, we include all the important photoionization edges of H, He, and the ions of C, N, O, and Ne that are present for T_e between 10^5 and 10^6 K (i.e., C IV–C VI, N IV–N VII, O IV–O VIII, and Ne IV–Ne X). A complete grid of models and a full list of photoionization edges will be given in Vennes & MacDonald (1991), together with comparisons with earlier work.

3.3 *Results*

For comparison with the X-ray observations of classical novae, we have calculated the expected count rates for the *EXOSAT* Lexan and Boron filters, and the *ROSAT* HRI, PSPC, and PSPC with a Boron filter. In Figure 1 we show the count rates as a function of temperature for the two representative compositions, for an assumed distance of 2 kpc and an interstellar column density of 4×10^{21} cm^{-2}, parameters which are typical of the three novae observed by OKB. Also shown are the ratios of Lexan to Boron count rates for *EXOSAT* and PSPC to PSPC with Boron filter for *ROSAT*. These ratios are useful for determining an X-ray color temperature for the stellar remnant.

From the figures we can make the following deductions: (1) For $T_e > 5 \times 10^5$ K the count rates are relatively insensitive to T_e, and accurate determination of the maximum temperature requires high signal to noise and a very precise distance estimate. (2) If the distance to the nova is well determined from the maximum magnitude–rate of decline relation and there is an estimate of $N_{\rm H}$, it is possible to distinguish between Ne-rich and Ne-poor atmospheres in the effective temperature range 250,000 to 500,000 K.

4. THE *EXOSAT* OBSERVATIONS

For QU Vul 1984, there are simultaneous exposures with the Lexan and Boron filters, 307 days after optical maximum. Using the distance and hydrogen column density given by OKB, T_e can, in principle, be estimated from the ratio of Lexan to Boron count rates for each assumed composition. From the 1 σ error estimates, this ratio is between 1.0 and 7.6. For either composition, this requires T_e greater than $\sim 8 \times 10^5$ K. At this

TABLE 1

CHEMICAL COMPOSITION OF THE MODEL ATMOSPHERES

	Mass Fractions					
Model	H	He	C	N	O	Ne
A: CO White Dwarf (Cyg 75, 78)	0.47	0.22	0.059	0.11	0.13	0.015
B: ONeMg White Dwarf (CrA 81)	0.31	0.31	0.0046	0.080	0.12	0.17
C: Sun	0.74	0.24	0.0039	0.00094	0.0088	0.0021

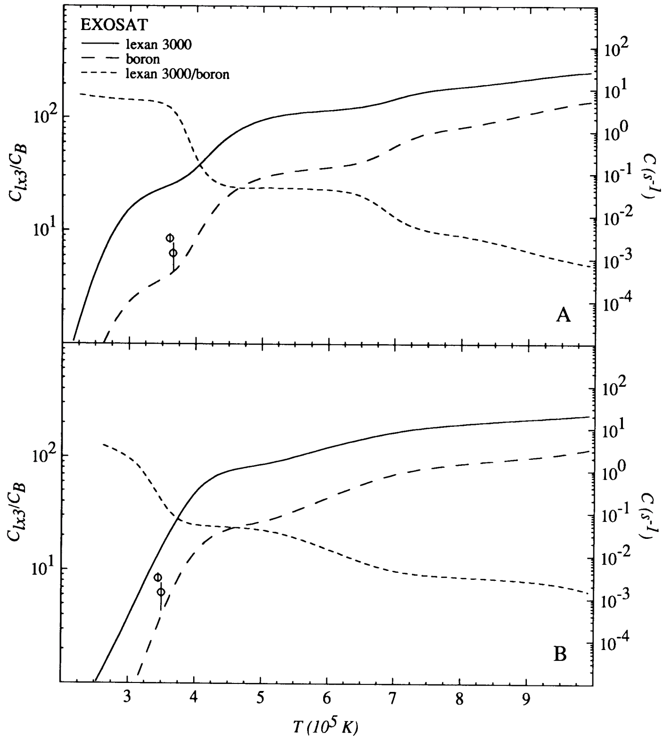

FIG. 1*a*

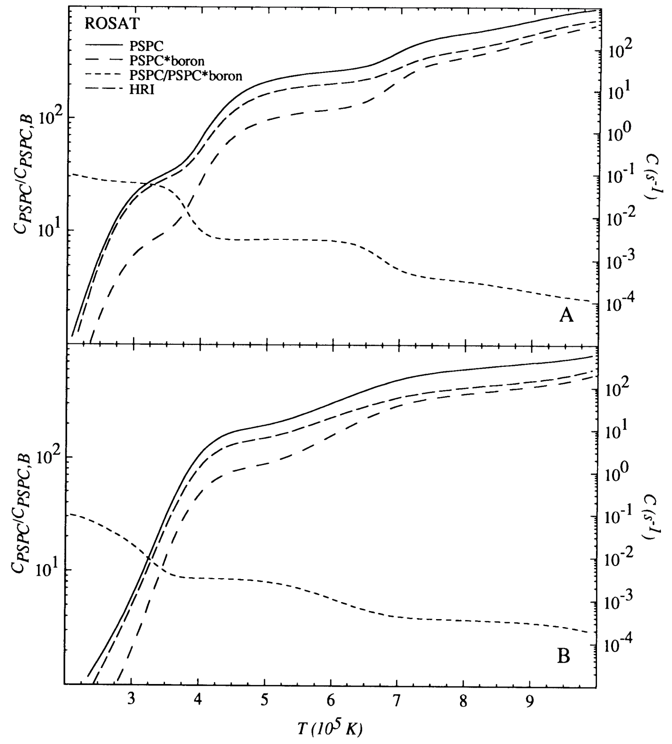

FIG. 1*b*

FIG. 1.—(*a*) *EXOSAT* count rates plotted against effective temperature in units of 10^5 K. Also shown is the ratio of count rate with the thin lexan filter to count rate with the boron filter. The circles indicate the count rates for Nova QU Vul 1984, 307 days after optical maximum. (*b*) Predicted *ROSAT* count rates plotted against effective temperature. Also shown is the ratio of the predicted PSPC count rate to the PSPC count rate with boron in place. In each figure, the top panel corresponds to composition A and the lower panel to composition B. The assumed hydrogen column density and distance are $N_H = 4 \times 10^{21}$ cm^{-3} and 2 kpc, respectively.

temperature, the predicted count rates are many orders of magnitude greater than observed. Making use of the Lexan count rates alone, for the assumed distance and N_H, gives $T_e \simeq 2.7 \times 10^5$ K for metals A and $T_e \simeq 3.2$–3.3×10^5 K for metals B. The Boron count rates alone give $T_e \simeq 3.6$–3.9×10^5 K for metals A and $T_e \simeq 3.5$–3.7×10^5 K for metals B. Clearly the discrepancy between temperature estimates is much less for metals B, which is consistent with the abundance determinations for this object. Better agreement might be obtained if we explore a larger range of composition parameters, interstellar hydrogen column density, and distance. Other possibilities are that the difference in temperature estimates may be due to absorption in a wind from the remnant or the presence of a small amount of nonthermal emission.

Hence, if there is an independent estimate of the plateau luminosity, for example, from UV or infrared observations, the X-ray data can be used to discriminate between neon-rich and neon-poor novae. In addition, by comparing with pure helium atmosphere models, the X-ray data shows directly that the remnant envelope itself is enriched in metals, independently of the nebula analysis. The Lexan count rate for this nova 192 days earlier shows that the effective temperature increased by ~14,000 K over this time interval, giving an *e*-folding time for T_e of ~12 yr. Similarly the variations in count rates for GQ Muscae indicate temperature variations of the same magnitude over similar time intervals. In particular, the apparent "turnoff" of GQ Muscae 914 days after optical maximum (OKB) may be due to a drop in T_e of ~4%. The analysis of the nebula emission lines by Krautter & Williams (1989) indicates that the remnant was still hot and luminous 5.5 yr after optical maximum, which is consistent with the results of MacDonald et al. (1985), if M_{WD} is greater than ~1.1 $M_\odot$.

5. *ROSAT* PREDICTIONS

For *ROSAT* the PSPC to PSPC ratio is a less sensitive temperature indicator than the Lexan to Boron ratio was for

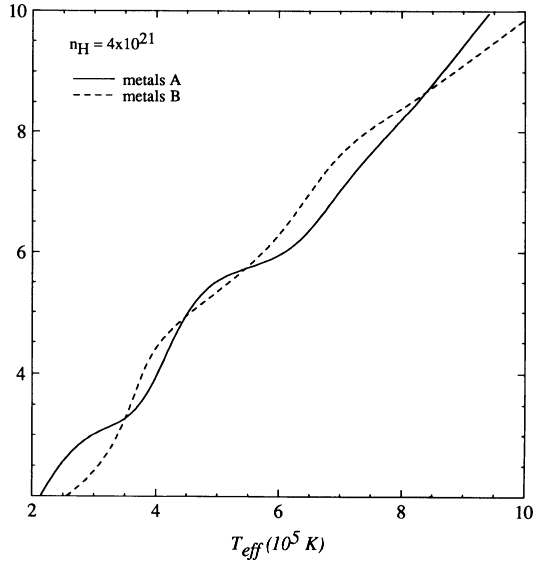

FIG. 2.—Equivalent blackbody temperature, T_{BB}, against effective temperature, T_{eff}, as determined from the predicted *ROSAT* PSPC count rates, T_{BB} and T_{eff} are in units of 10^5 K.

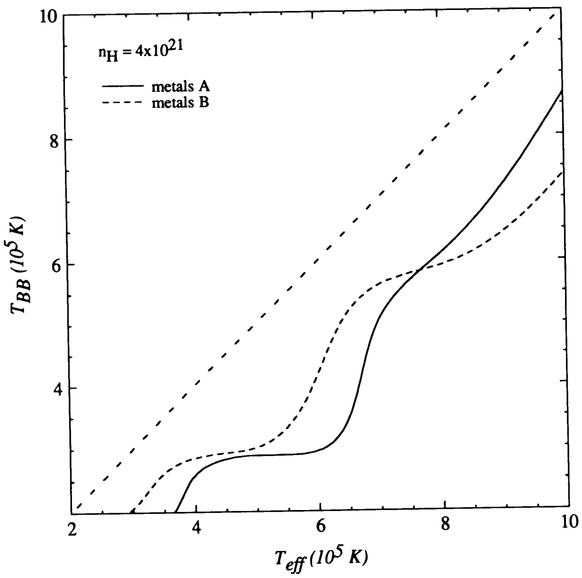

FIG. 3.—Equivalent blackbody temperature, $T_{\rm BB}$, against effective temperature, $T_{\rm eff}$, as determined from the ratio of *ROSAT* PSPC to PSPC with boron filter count rates. $T_{\rm BB}$ and $T_{\rm eff}$ are in units of 10^5 K. A dashed diagonal line is included for comparison purposes.

EXOSAT. However, this is somewhat compensated for by the greater efficiency of *ROSAT* which will give a better signal to noise ratio. Again, observations with and without the boron filter are essential to discriminate between different envelope abundances. This is most effective for $T_e < 500{,}000$ K.

In view of the fact that OKB used blackbody temperatures to interpret the *EXOSAT* X-ray data, we have compared the count rates for the model atmospheres with those for blackbodies. We show in Figure 2, the temperature of the blackbody that gives the same *ROSAT* PSPC count rate as the model atmosphere as a function of the effective temperature of the atmosphere. It can be seen that the blackbody temperature is a reasonable approximation with maximum errors of $\sim 20\%$. In Figure 3, we show the temperature of the blackbody that has the same ratio of PSPC to PSPC plus boron filter count rates as the model atmosphere. Now the blackbody temperature can be a gross underestimate, by as much as a factor of 2, of the true effective temperature. Clearly, unless the distance to the nova is known very accurately, the model atmosphere calculations are necessary to interpret *ROSAT* observations.

6. SUMMARY

In this *Letter*, we present the results of applying the first calculations of model atmospheres in LTE and hydrostatic equilibrium for stars very close to the Eddington limit, to the stellar remnants of classical novae in optical decline. We show that these stars should be copious emitters of EUV and soft X-rays, even for high metallicity, and conclude that such model atmosphere calculations are necessary for interpretation of forthcoming *ROSAT* data.

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