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THE SOFT X-RAY TURNOFF OF NOVA MUSCAE 1983

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ABSTRACT

Nova GQ Muscae 1983 was detected by *ROSAT* as a luminous "supersoft" X-ray source in 1992, nearly a decade after outburst. Further, this is the only classical postnova known to have maintained constant luminosity on a timescale predicted by theoretical models. Follow-up observations were made with the *ROSAT* position-sensitive proportional counter in 1993 January and September, and complemented with *B*-band photometry taken in 1993 January. By 1993 January, the X-ray count rate had declined by a factor of 17, while there was neither an appreciable decrease in the optical magnitude nor a change in the amplitude of modulation. In 1993 September the soft X-ray flux was below the *ROSAT* threshold limit, implying a decrease of a factor ≥ 30 in the count rate. This decline can be interpreted by the turnoff of nuclear processes due to the complete consumption of the residual hydrogen-rich envelope. However, the optical luminosity of the system is not simply coupled to the X-ray luminosity (e.g., through reprocessing).

Subject headings: binaries: close — novae, cataclysmic variables — stars: individual (GQ Muscae)

1. INTRODUCTION

The nuclear-burning lifetimes of postnovae are still a point of contention. Most standard theoretical models predict that hydrogen burning continues on the white dwarf surface for at least a decade after outburst (Prialnik 1986; Kato & Hachisu 1989). Yet observations typically indicate that the postoutburst luminosities decline, and thus H-burning shell sources turn off, in classical novae within a few years. The *ROSAT* all-sky survey provided an opportunity for short observations of 286 postoutburst Galactic novae (Orio et al. 1992a). Subsequently, longer pointed observations of 10 LMC and 20 Galactic novae were performed with *ROSAT* (Orio 1993; Ögelman 1994). Of these, only two, Nova GQ Muscae 1983 and Nova Cygni 1992, observed 9 years and 1 year after outburst, respectively, appeared as very luminous supersoft X-ray sources. Nova Cygni 1992, however, turned off in the course of the following year (Krautter et al. 1994). Effectively, the theoretically anticipated multiple-year, constant bolometric luminosity nuclear-burning phase was demonstrated only by GQ Mus (Ögelman et al. 1993).

These results imply that most classical novae deplete their accreted hydrogen-rich envelopes rather quickly. The radiatively driven wind from the white dwarf (see Prialnik, Shara, & Shaviv 1978; Kato 1983a, b) might remove the envelope effectively. The frictional interaction between the expanding envelope and the companion star (MacDonald 1980; Livio et al. 1990), or magnetic rotator effects (Orio, Trussoni, & Ögelman 1992b), also can remove mass from a postnova. As GQ Mus does *not* follow this trend, it offers an opportunity to investigate a nova where the expected long-duration nuclear-burning phase appears to have occurred, and now possibly has ended after almost a decade.

What is different about GQ Mus in comparison with most other novae? As suggested by Ögelman et al. (1993), one important factor may be the short orbital period of GQ Mus and the small secondary mass which may have enhanced the effects of irradiation of the secondary, which in turn induced continued accretion onto the white dwarf surface and prolonged the active phase. Ögelman et al. also noted the similarity between the X-ray properties of GQ Mus and those of the supersoft LMC X-ray sources CAL 83, CAL 87, and RX J0527.8−6954 (Greiner, Hasinger, & Kahabka 1991). The supersoft sources can be explained by hydrostatic thermonuclear burning of hydrogen accreted onto white dwarfs from 1.5–2.0 $M_\odot$ main-sequence companions (van den Heuvel et al. 1992). Care must be taken in this comparison, however, as GQ Mus is a short-period binary system whose secondary is much less massive than the primary ($M_s \leq 0.2\ M_\odot$; Diaz & Steiner 1994). Thus, the relationship between renewed accretion and nuclear burning could be one critical factor in the postoutburst evolution of GQ Mus.

In this paper we present *ROSAT* position-sensitive proportional counter (PSPC) observations, performed in 1993 January and September, and *B*-band CCD photometry obtained contemporaneously with the January *ROSAT* observations. Section 2 describes the results suggesting that GQ Mus has turned off as a luminous X-ray source, and § 3 discusses the implications of these observations.

2. OBSERVATIONS AND RESULTS

2.1. *ROSAT Observations*

Nearly a year after its discovery by *ROSAT* as a luminous "supersoft" X-ray source (Ögelman et al. 1993), GQ Mus was observed again with the *ROSAT* PSPC, once during 1993 January 7–11 with an effective exposure time of 4296 s and once during 1993 August 23–September 3 with an effective exposure time of 10,091 s. The observed X-ray flux from

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GQ Mus decreased sharply in these follow-up observations. Although the count rate in 1992 February was 0.108 ± 0.004 counts s^{-1}, the rate had dropped to 0.0065 ± 0.0018 counts s^{-1} by 1993 January. GQ Mus was not detected during the 1993 August–September observations at a 3 σ upper limit of 0.0028 counts s^{-1}. Table 1 summarizes these results.

The *ROSAT* PSPC is a gas-filled proportional counter, sensitive over the energy range 0.1–2.4 keV, with energy resolution $\Delta E/E \sim 0.43$ at 0.93 keV (for further details of the satellite and the X-ray telescope see Trümper 1983). The initial 1992 February *ROSAT* observation had a sufficient number of detected photons to perform a spectral fit and show that a blackbody spectrum with an effective temperature of 3.3×10^5 K gives a satisfactory fit to the data. The fitted flux values in turn corresponded to a white dwarf with photospheric radius of $\sim 3 \times 10^9$ cm at the estimated distance of 4.7 kpc (Krautter et al. 1984) radiating near the Eddington luminosity range of $\sim 10^{38}$ ergs s^{-1} (Ögelman et al. 1993). The limited number of photons collected from GQ Mus during the follow-up observations (about 27 for 1993 January and none for 1993 August–September exposures) allows spectral fits for a wide range of models. However, a cursory look at the pulse-height distribution of the 1993 January data revealed that the detected photons are all below ~ 0.7 keV and indicated that GQ Mus is still a soft source. The blackbody fit parameters, however, had changed.

To examine the development of GQ Mus in effective temperature versus bolometric flux parameter space (i.e., the Hertzsprung-Russell diagram), we determined the contours of confidence allowed by the data. Since the interstellar column density parameter N_H is not expected to change, it was kept fixed at the value 2.5×10^{21} cm^{-2} in order to limit the spread of contours and see the relative development of the blackbody model contours more clearly. In Figure 1 we plot the 1 σ contours of the allowed blackbody parameters resulting from the spectral fits to the follow-up observations; in addition, the initial 1992 February data is reanalyzed at the fixed N_H. Also shown on the plot are the constant-radius lines of a blackbody as well as the Eddington limited flux of a 1 $M_\odot$ object at a distance of 4.7 kpc. The 30% error in the distance estimation and the real mass of the white dwarf will cause the radius and bolometric flux lines to move in the plot; however, Figure 1 properly represents the *relative* development of the blackbody parameters.

From the contour lines in Figure 1 we see that at least two possible origins for the observed decrease of the X-ray flux of GQ Mus exist: either the white dwarf is cooling at a constant radius, or its photospheric radius has increased (temperature slightly decreased) while staying on the constant bolometric luminosity track. The latter behavior could be a result of mass

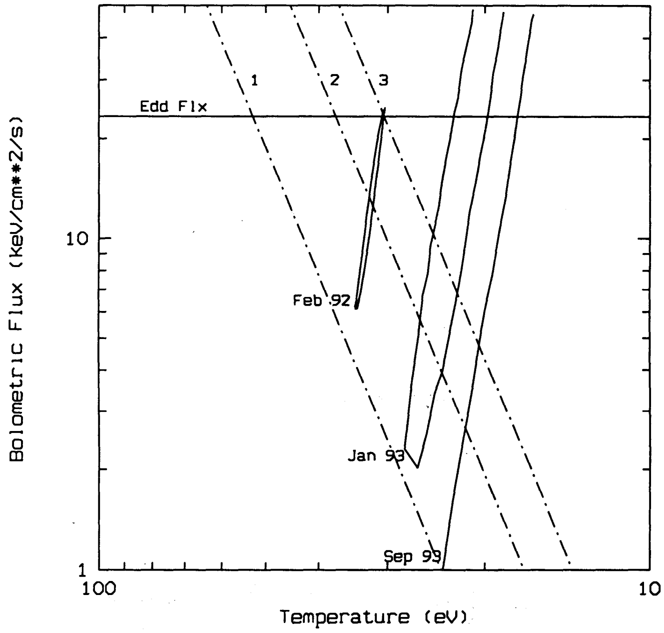

FIG. 1.—One sigma contours of the blackbody model fit in the bolometric flux–effective temperature plane (holding $N_H = 2.5 \times 10^{21}$ cm^{-2}) are plotted for the 1992 February and 1993 January observations. The 1 σ upper limit line for 1993 September is also given. The Eddington limit flux for $L = 10^{38}$ ergs s^{-1} at a distance of 4.7 kpc is indicated on the graph as a solid horizontal line. Blackbody radius curves (for 1×10^9, 2×10^9, and 3×10^9 cm) are plotted as dot-dash lines.

transfer from the secondary leading to the bloating of the overfed white dwarf.

Interpreting the data as representing an extinguished white dwarf cooling on a constant-radius track, we can obtain a cooling timescale τ_{cool}, where $T = T_0 \exp -t/\tau_{cool}$. For the case of a blackbody radius of 2×10^9 cm, the temperatures derived from Figure 1 are ~ 32, 25, and less than 21 eV for 1992 February, 1993 January, and 1993 August–September data, respectively; the implied cooling timescale is $\tau_{cool} \simeq 3.3$ yr. Similar considerations for a 3×10^9 cm radius gives $\tau_{cool} \simeq$ 3.9 yr. Despite a wide range of spectral fit parameters, it is interesting that the physical constraints restrict the cooling time to a range of 3–4 yr.

2.2. *Optical Photometry*

Johnson *B*-band CCD observations of GQ Mus were obtained with the CTIO 0.9 m telescope on 1993 January 22. These data were taken as a series of 10 5 minute exposures with a Tektronix 512 × 512 CCD covering an interval of 59 minutes (69% of an orbital period). The data were reduced and analyzed by standard methods with IRAF to yield a light curve relative to field stars with an internal error of ± 0.02 mag. During our observations GQ Mus was observed to vary by 0.96 mag, which is comparable to the variability reported from earlier epochs by Diaz & Steiner (1990, 1991, 1994). The shape and amplitude of the light curve appear to have changed little in the early 1990s.

The data were transformed to Johnson *B* magnitudes via observations of six Landolt (1992) standards in the Rubin 149 field. Because of the limited time which could be devoted to this project, the extinction and color terms were not well deter-

TABLE 1

JOURNAL OF OBSERVATIONS AND DETECTED COUNT RATES FOR GQ MUSCAE

Date	Exposure Time (s)	Observed Count Rate $\pm 1\ \sigma$ (counts s^{-1})
1992 Feb 25–26..........	5840	0.108 ± 0.004[a]
1993 Jan 7–11...........	4296	0.0065 ± 0.0018
1993 Aug 23–Sep 3......	10091	≤ 0.0028 (3 σ)

[a] From Ögelman et al. 1993.

mined, and the B magnitude may have zero-point errors of ± 0.2 mag. These observations are again similar to results reported for 1989 and 1990 by Diaz & Steiner (1994), and suggest that by early 1993 the nova had not become dramatically fainter in the optical band. An additional B-band CCD image taken on 1994 February 21 by G. Massone (1994, private communication) at ESO demonstrates that, remarkably, the nova is at least as optically bright in early 1994 as it was in 1993 January. Even so, the optical power amounts to only $\sim 10\ L_\odot$ and thus is only a small fraction of the bolometric luminosity.

3. DISCUSSION

GQ Mus turned off as a soft X-ray source between early 1992 and late 1993. During this decline the effective blackbody temperature apparently dropped from 30 eV in 1992 February to 15–29 eV in 1993 January. We must consider the important effects that temperature changes will have on the X-ray flux. Because *ROSAT* samples the Wien side of the energy distribution, the blackbody flux will decline exponentially as $e^{-E/kT}$ (Ögelman 1989). Thus, the factor of ≥ 30 decline in *ROSAT* count rate could be produced by a factor of ≥ 3 change in effective temperature, from 350,000 to 150,000 K *with no change in bolometric luminosity*.

The evolution of the bolometric luminosity of GQ Mus, therefore, cannot be answered on the basis of *ROSAT* observations alone. If we identify the X-ray source in GQ Mus with the hot photosphere of a postoutburst white dwarf star, then a temperature decline could result either from evolution at constant luminosity toward a larger radius or from a luminosity turnoff in which both L and radius decline as the white dwarf moves onto a standard constant-radius cooling track. Did either of these standard possibilities occur in the case of GQ Mus?

If GQ Mus cooled at near-constant luminosity, then the peak of its energy distribution must shift into the extreme ultraviolet (EUV) spectral region, where it cannot be directly observed. Fortunately, the nova is surrounded by a nebular shell, has a companion star, and quite possibly is experiencing accretion (e.g., Diaz & Steiner 1994; Idan, Shaviv, & Starrfield 1994), although we believe that nuclear burning probably significantly contributed to the UV luminosity (see González-Riestra, Orio, & Gallagher 1994). All of these components likely reprocess the radiation from a luminous source. Thus, if the white dwarf component of a nova remains luminous, we would expect only a modest dip in the ionization levels of the ejecta in the shell. Krautter & Kneer (1994) obtained optical spectra indicating that the decline in ionization has been dramatic (see also Krautter & Williams 1989; Péquignot et al. 1993; Hamuy, Phillips, & Williams 1994); [Fe X] has disappeared, and low-ionization [N II] emission is now seen. The qualitative behavior of the nebular spectrum agrees with the interpretation that both the temperature and the luminosity of the ionizing radiation source in GQ Mus have dropped.

In principle, the optical and far-UV spectrum will reflect some combination of emission of direct or reprocessed light from the hot white dwarf as well as light produced from gravitational potential energy released during accretion. Optical and far-UV spectra are not straightforward to interpret in GQ Mus during the postoutburst stage. This is especially true with respect to the nature, luminosity, and spectrum of radiation produced from accreting matter, which Diaz & Steiner (1994) have argued is located in an accretion column as in a AM Herculis–like (or polar) system. Indeed, the double-peaked light curve which occurs on the orbital period suggests some form of asymmetry in the system, such as an accretion column (Diaz & Steiner 1989, 1990) or an elliptical accretion disk, which evidently continued after the X-ray turnoff. As demonstrated by Diaz & Steiner, accretion flows can have large radiating areas that allow them to produce and reprocess light and can be important long-wavelength luminosity sources. Furthermore, accretion structures can be asymmetrically placed within the nova system. However, the Diaz & Steiner model requires huge mass transfer rates in order to yield the observed copious soft X-ray flux from GQ Mus. Until the complex relationship between the soft X-ray power source and other light sources in the system is sorted out, we cannot easily use the longer wavelength data to constrain the state of GQ Mus.

The best explanation at present for GQ Mus, therefore, is that both temperature and luminosity have dropped because the long-term quasi-static nuclear burning, predicted by theoretical models to occur over multiyear timescales in classical novae (e.g., Ögelman et al. 1993; MacDonald & Vennes 1991), finally ceased. In this case we wonder why GQ Mus remained a luminous soft X-ray source for so much longer than other recent novae. The observations again support two possibilities. First, the ejected mass appears to have been low, $\approx 10^{-5}\ M_\odot$ (Krautter et al. 1984). After its outburst, GQ Mus simply may have had more material left on its white dwarf which could support long-term nuclear burning, in which case about $\sim 3 \times 10^{-6}\ M_\odot$ would have been converted into He by the burning shell.

A second option is that the nova's nuclear fuel was resupplied via accretion. Diaz & Steiner (1994) have made a strong case for the importance of accretion in determining the optical spectra and light variability of GQ Mus. If the accretion rate were sufficiently large ($\geq 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$; Iben 1982, Kato & Hachisu 1989), then the burning would be stable and the star could burn for a long time. At slightly higher rates the accreting white dwarf would build up a surface shell and become cooler, which is a possible physical mechanism to produce constant-luminosity cooling. But perhaps most relevant is the possibility of accretion at rates somewhere below the critical value for sustained nuclear burning that could extend the lifetime of the postoutburst burning phase to slightly more than a decade.

This possible unusual linkage between accretion and nuclear burning could be due to the short orbital period of 85.5 minutes for GQ Mus (Diaz & Steiner 1990), which places the secondary very close to the primary. Under these circumstances irradiation of the secondary during the nova outburst might be abnormally effective in enhancing mass transfer (e.g., Kovetz, Prialnik, & Shara 1988; Shaham et al. 1993). For example, the hemisphere of the secondary star which faced the white dwarf should have reached a temperature of about 80,000 K (see also Diaz & Steiner 1994) during the soft X-ray phase of the nova, and thereby have contributed to both the UV and the optical light curves, while also being stimulated to expand and transfer mass.

While the positive-feedback model where irradiation induces mass transfer to fuel nuclear burning has attractive features, there are still some important points which remain to be clarified. We need to quantify the turnoff model to see whether the luminosity and temperature of the white dwarf are likely to respond on observed timescales. Also significant to consider are the polar-like optical light curve and the nearly constant mean optical luminosity which are seemingly independent of the X-ray source. This raises the possibility that some of the features of GQ Mus are associated with polar accretion phenomena, which include complex variability (Cropper 1990). However unlikely, the X-ray decline in GQ Mus might be ascribed to some form of strong X-ray variability, like that which some supersoft X-ray sources have exhibited. Furthermore, as it appears that GQ Mus is continuing to accrete, it is not inconceivable that GQ Mus may resume nuclear burning. We would like to combine accretion and burning models quantitatively by properly describing irradiation within this binary star system.

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