THE ASTROPHYSICAL JOURNAL, 408:L5–L8, 1993 May 1

THE SECONDARY MAXIMA IN BLACK HOLE X-RAY NOVA LIGHT CURVES: CLUES TOWARD A COMPLETE PICTURE

WAN CHEN,[1,2] MARIO LIVIO,[3,4] AND NEIL GEHRELS[1]
Received 1993 January 19; accepted 1993 February 19

ABSTRACT

We study the *secondary maxima* observed commonly in the X-ray/optical light curves of black hole X-ray novae and show that they can play an important role in our understanding of the X-ray nova phenomenon. We discuss the observational characteristics of the secondary maxima and possible mechanisms to produce them. We propose a complete scenario for black hole X-ray nova events. The main outburst is caused by a disk instability. The second maximum is caused by X-ray evaporation of the matter near the inner Lagrangian (L_1) region when the disk becomes optically thin. The third maximum (or the final minioutburst) is due to a mass transfer instability caused by hard X-ray heating of the subphotospheric layers of the secondary during the outburst. We predict that the newly discovered X-ray nova GRO J0422+32 may develop a final mini-outburst in early 1993 and that its binary orbital period is less than 7 hr.

Subject headings: accretion, accretion disks — binaries: close — black hole physics — X-rays: stars

1. INTRODUCTION

X-ray novae (soft X-ray transients) are a special subclass of low-mass X-ray binaries (LMXBs), in which it is thought that nonsteady mass transfer onto a compact primary (via an accretion disk) causes sporadic and sometimes repetitive large outbursts, with typical recurrence times between 1 and 60 yr (e.g., Bradt & McClintock 1983; White 1992). There exists strong evidence that a large fraction of the X-ray nova systems may contain a black hole, and in fact all known LMXB black hole candidates are bright X-ray novae (e.g., Cowley 1992). The X-ray flux of most X-ray novae (especially those containing black hole candidates) is usually very low during quiescence (e.g., Mineshige et al. 1992). At outburst, it may increase by more than five orders of magnitude in a few days, and then decay exponentially on a time scale of a few months (e.g., White, Kaluzienski, & Swank 1984).

On the basis of the different mechanisms that regulate the accretion flow onto the primary there are two competing models for the outbursts of X-ray novae. The mass transfer instability model (MTI; Hameury, King, & Lasota 1986, 1988, 1990) suggests that the outburst is due to a sudden increase of the mass transfer rate *from the secondary star*. This happens when the stellar surface, which is heated by continuous hard X-ray irradiation from the central region of the disk during quiescence, expands to within a critical distance of the L_1 point. The disk thermal instability model (DTI; Lin & Taam 1984; Huang & Wheeler 1989; Mineshige & Wheeler 1989), on the other hand, attributes the outburst to a sudden increase of the mass transfer rate *through the accretion disk*. This occurs when the disk surface density, which increases during quiescence, exceeds the threshold to trigger a thermal instability (due to a sharp increase of the temperature-sensitive opacity of a partially ionized gas). Both models can, under certain assumptions, roughly reproduce the recurrence time scale and the light curve during both rise and early decline.

There are, however, two important pieces of evidence which suggest that the outburst is caused by the disk instability mechanism. First, observations of A0620−00 and X-Ray Nova Muscae 1991 (XN Mus, also GS1124−683), both known to be black hole candidates, show that the rise in hard X-rays precedes the rise in soft X-rays (Ricketts, Pounds, & Turner 1975; Brandt et al. 1991). This is consistent with a DTI model in which the outburst starts from the hot *inner* part of the disk for systems having low accretion rates at quiescence (Smak 1984; Huang & Wheeler 1989). It is more difficult (though not impossible) for the MTI model to reproduce such a delay in the soft X-ray flux, because the mass transfer outbursts always start from the cool *outer* part of the disk. Second, in order to trigger the main outburst in the MTI model, the hard X-ray flux at the L_1 point has to exceed the stellar flux. Therefore, the quiescent hard X-ray luminosity has to be larger than $\sim 2.5 \times 10^{34}$ ergs s^{-1} M_s^2 (Hameury et al. 1986; Mineshige et al. 1992), where M_s is the secondary mass in solar units. The observed upper limits of quiescent X-ray fluxes for most black hole X-ray novae (BHXNs) is well below this value (e.g., Mineshige et al. 1992).

Nevertheless, more observational and theoretical studies are needed to form a complete picture. There are indeed some important features in BHXN light curves, namely, the *secondary maxima*, which the existing models have not yet attempted to explain. These features may hold important clues toward a full understanding of the BHXN phenomenon. In this *Letter* we study the *secondary maxima* and examine the question of whether a self-consistent scenario for the entire behavior of BHXNs, including both the main outburst and the secondary maxima, can be constructed.

2. SECONDARY MAXIMA IN X-RAY NOVA LIGHT CURVES

About 2 months after the main outburst, some BHXNs develop a *second maximum* in their X-ray light curves: the flux starts to rise slightly for about 10 days and then decays at roughly the same rate as before (Fig. 1, *upper panel*). The devi-

[1] NASA/Goddard Space Flight Center, Greenbelt, MD 20771.
[2] Universities Space Research Association.
[3] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.
[4] Department of Physics, Technion, Haifa 3200, Israel.

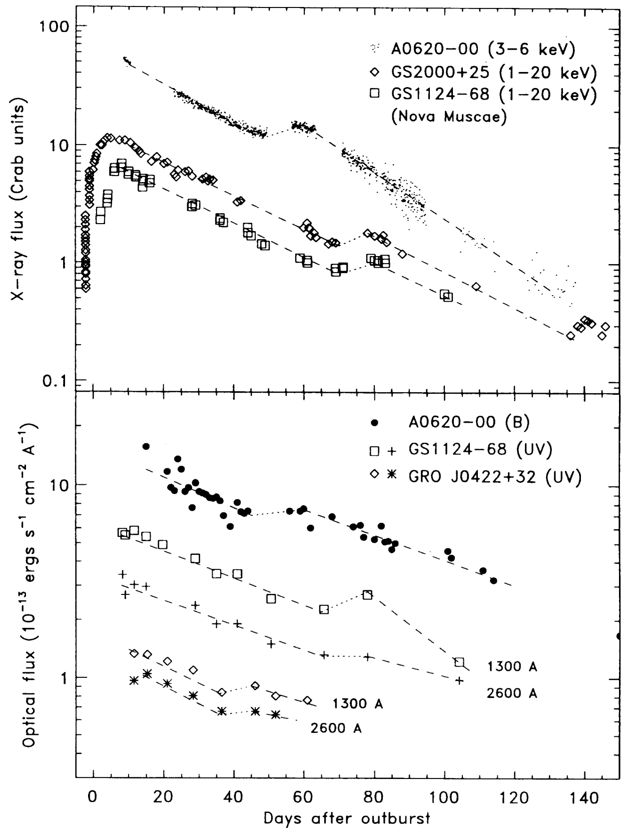

FIG. 1.—X-ray and UV/optical light curves of the black hole X-ray novae A0620−00 (Kaluzienski et al. 1977; Tsunemi et al. 1977), GS 2000+25 (Tanaka et al. 1991), GS 1124+68 (Tanaka et al. 1991; Shrader & Gonzalez-Riestra 1991), and GRO J0422+32 (Shrader et al. 1993). A second maximum at about 2 months after the outburst is apparent in all the light curves. Each light curve is fitted with an exponential decay law (*dashed line*) at periods both before and after the second maximum. The transition in the second increase phase is drawn arbitrarily (*dotted line*) because of lack of data. For clarity, the UV/optical light curves of A0620−00 and GRO J0422+32 have been multiplied by factors of 10 and 3, respectively.

ation from the extrapolation of the preincrease flux is usually less than a factor of 2. The delay between the main outburst (the primary maximum) and the second maximum is ~55 days in A0620−00 (Kaluzienski et al. 1977), and ~75 days in *both* GS 2000+25 (Tsunemi et al. 1989) *and* XN Mus (Tanaka, Makino, & Dotani 1991). As shown in the lower panel of Figure 1, a similar feature appeared in the UV/optical light curves of A0620−00 (Tsunemi, Matsuoka, & Takagishi 1977) and XN Mus (Shrader & Gonzalez-Riestra 1991). We note that, in XN Mus, the increase in the longer wavelength (2600 Å) is less prominent than that in the shorter wavelength (1325 Å), i.e., the UV spectrum is hardened during the second maximum (Shrader & Gonzalez-Riestra 1991).

These observations suggest that the second maximum may be generic to BHXN light curves. The evidence became even more compelling when a similar feature was observed ~45 days after the outburst in the UV light curves of the newly discovered GRO J0422+32 (Shrader et al. 1993), another BHXN candidate from its spectral behavior. In fact, the magnitude and wavelength dependence of the second maximum in J0422+32 are almost identical to those in XN Mus (Fig. 1).

Another important feature, a *third maximum*, was observed in the X-ray/optical light curves of A0620−00, in the form of a final minioutburst which occurred ~200 days after the main

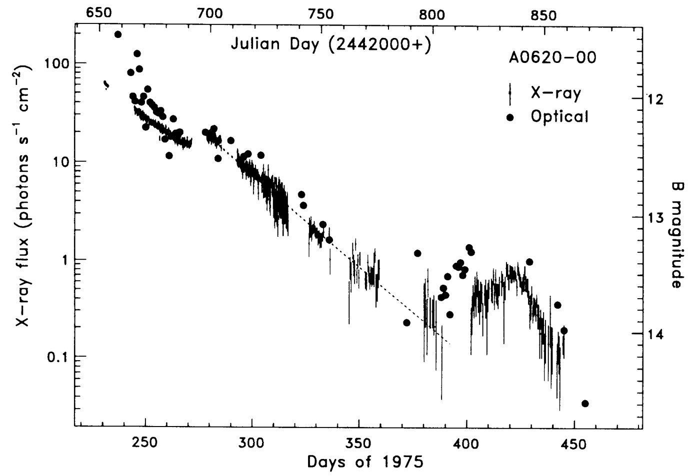

FIG. 2.—Comparison of the long-term X-ray and optical light curves of A0620−00 (Kaluzienski et al. 1977; Tsunemi et al. 1977). The vertical scale for the X-rays is at the left-hand axis, and for the optical it is at the right-hand axis. The plot is made by aligning the best-fit post–second-maximum decay profile (*dashed line*) in the X-rays with that in the optical. A final minioutburst (the third maximum) is seen in both X-ray and optical at about 170 days after the main outburst. It is also seen that the optical flux rises before the X-rays during the final minioutburst.

outburst (Kaluzienski et al. 1977; Tsunemi et al. 1977). As shown in Figure 2, the X-ray/optical flux reached a local maximum in about 30 days and then decayed rapidly. The flux was essentially cut off about 30 days after the maximum. The peak flux of the minioutburst was more than an order of magnitude above the extrapolation of the exponential decline, although the total energy involved was only ~1% of the total energy released during the entire X-ray nova event. There is evidence that a similar but less prominent feature appeared also in the X-ray light curve of XN Mus (K. Ebisawa, private communication).

3. THEORETICAL INTERPRETATION

3.1. *The Second Maximum*

The total energy released in the second maximum in XN Mus can be estimated as follows. The observed X-ray flux (Tanaka et al. 1991) after the second increase is approximately $4.7 \times 10^{-8} \exp(-t_d/28)$ ergs s^{-1} cm^{-2}, and the flux extrapolated from the preincrease phase is $\sim 2.5 \times 10^{-8} \exp(-t_d/28)$ ergs s^{-1} cm^{-2}, where t_d is the time in days after the main outburst. So the extra energy associated with the second maximum, integrated from its onset (70 days) to the beginning of the third maximum (180 days), is $E_{\rm sm} \sim 8.4 \times 10^{42} D^2_{5\,\rm kpc}$ ergs, where $D_{5\,\rm kpc}$ is the distance in units of 5 kpc. This extra energy corresponds to an amount of extra mass of $\Delta M \sim 9.3 \times 10^{22}(\eta/0.1) D^2_{5\,\rm kpc}$ g that has to be accreted onto the black hole during the second maximum, where $\eta = 0.1$ is the efficiency of X-ray production.

The shape of the light curves before and after the second maximum suggests that this extra mass is *added* to the disk during the second increase and then the accretion resumes its "normal" decay afterward (although a slight change in slope is observed in A0620−00). We propose that the extra mass comes from the secondary, when its upper atmosphere, heated by the X-ray irradiation during the outburst, overflows the L_1 point. The mass outflow rate at the L_1 point is $\dot{M}_{L_1} \sim 3.1 \times 10^{16} P_{\rm hr} T_4 e^{-(\Delta r/H)^2}$ g s^{-1}, where $P_{\rm hr}$ is the orbital period in hours, T_4 the temperature at the L_1 point in 10^4 K, Δr the depth of the upper atmosphere below the L_1 point, and H the scale height at the L_1 point (Hameury et al. 1986). For XN Mus, $P_{hr} = 10.5$ and $T_4 = 1.8 L_{X,37}^{1/4}$, so the total mass transferred during the second increase (~10 days) is $\sim 5.1 \times 10^{23} e^{-(\Delta r/H)^2}$, in agreement with the required ΔM above. Since the temperature of the gas which flows into the disk is between 1.8×10^4 K, the gas temperature while leaving the L_1 point, and 5×10^6 K, the shock temperature at the impact upon the disk, a more prominent second maximum is expected at wavelengths shorter than 2600 Å, as observed in XN Mus and GRO J0422+32.

For XN Mus, *Ginga* results show that the second maximum appeared only in soft X-rays (< 10 keV) but not in hard X-rays (Tanaka et al. 1991). A similar trend is seen in GRO J0422+32, where there is a second maximum in the UV but not in the BATSE hard X-ray (> 20 keV; Harmon et al. 1993) data. These observations imply that (1) the second maximum must be closely related to the accretion disk itself and (2) hard X-ray emission from the central region of the disk is not directly determined by the accretion rate in the disk.

The total amount of X-ray energy absorbed by the secondary prior to the second maximum is also consistent with the energy required to produce the second maximum. The fraction of the X-rays emitted from the vicinity of the black hole and absorbed by the secondary is $\eta_X \sim 1.6(1 - \beta)(R_s/a)^2$, where R_s is the radius of the companion, β is the X-ray albedo averaged over the stellar surface, and a is the separation of the binary. For XN Mus, $R_s/a \approx 0.46[q/(1 + q)]^{1/3} = 0.21$ (for a small mass ratio $q = M_s/M_* \approx 0.1$), and the total X-ray energy radiated during the outburst before the second maximum is $\sim 3.0 \times 10^{44} D_{5\,\mathrm{kpc}}^2$ ergs. Therefore, the energy absorbed by the secondary is $E_{abs} \sim 2.1 \times 10^{43}(1 - \beta) D_{5\,\mathrm{kpc}}^2$ ergs, which is larger than E_{sm} for $\beta \leq 0.6$.

Since the response time scale of the upper atmosphere of the secondary to the blast of X-rays is very short, $\tau_{th} \sim GM_s \Delta M/(R_s \eta_X L_X) \leq 10^3$ s, we suggest that the delay between the primary and the second maxima is due to *an effective shielding*, by the accretion disk, of the L_1 point from X-ray illumination for an extended period. Hameury et al. (1988) used this conjecture to provide a mechanism to stop the mass transfer instability before the outburst reaches its peak. We shall now estimate the expected duration of the shielding.

The accretion disk has a total mass of $\geq 10^{-9}(\eta/0.1)\, M_\odot$ at the beginning of the main outburst. This is estimated from the total energy released during the entire X-ray nova event (~10^{44} ergs). The radius of the L_1 nozzle is of order $\sim 2.5 \times 10^8 T_4^{1/2} P_{hr}$ cm (e.g., Livio 1992). The column density through the outer part of the disk, toward the nozzle's edge, is $\sim 10^{27}$ cm^{-2}. So the L_1 point can indeed be completely shielded at the beginning of the outburst, and for it to be irradiated by the X-rays, the disk has to lose a significant fraction of its mass. Since $\dot{M}_{disk} \leq 10^{-8}\, M_\odot$ yr^{-1} during the outburst, this will take at least 40 days, which is consistent with the observed time delay between the primary and the second maxima. We have calculated the disk column density time evolution in more detail using the scale height and density profiles of a standard accretion disk model (Shakura & Sunyaev 1973). The results are plotted in Figure 3 for A0620−00, for which the binary information is the most complete. We see that the height of the outer edge of the disk at the onset of the second maximum becomes smaller than the projected L_1 opening. Since the disk scale height is mainly determined by the separation of the binary, systems with longer orbital periods, such as XN Mus, will have a larger (and thicker) disk. A longer delay time

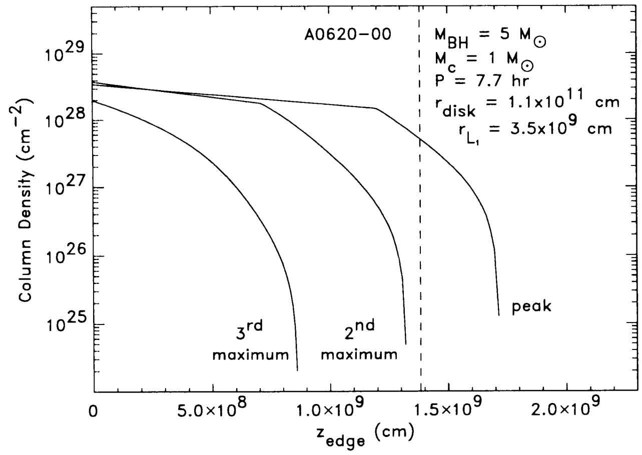

FIG. 3.—Column density through the accretion disk in A0620−00 toward the secondary as a function of the vertical distance above the disk. The binary parameters and the radii of the disk and the L_1 nozzle are shown in the plot. Three curves, as marked, represent the column density profiles when the system is at the peak of the outburst and at the beginning of the second and third maxima. The dashed line shows the radius of the L_1 nozzle projected onto the outer edge of the disk.

between the primary and the second maxima is then expected. This is consistent with the observations. Our model also predicts that the binary period in GRO J0422+32 will be less than 7 hr, since its second maximum occurred earlier than that in A0620−00. Recent photometry indicates a short orbital period of ~5.1 hr (Chevalier & Ilovaisky 1993; Kato, Mineshige, & Hirata 1993), which needs to be confirmed by further spectroscopic observations.

3.2. *The Final Minioutburst*

It is reasonable to believe that the third maximum is caused by a mass transfer instability of the secondary, since it is difficult to trigger a disk instability while the disk surface density is *decreasing*. In order to test this hypothesis, we have reconstructed the correct sequence of events (in the optical and X-rays) for A0620−00 during the rise to the third maximum. It is clearly seen in Figure 2 that the increase of the optical flux precedes that of the X-rays by a few days. This is exactly what would be expected in outbursts which start in the *outer* part of the disk, a characteristic of the MTI model.

One of the major objections (§ 1) against the MTI model as the mechanism for the main outburst in BHXNs is the lack of a substantial hard X-ray flux at quiescence (Mineshige et al. 1992). However, the energetics associated with the final minioutburst are fully consistent with the MTI model. The total energy involved in this event is only a few percent of the hard X-ray energy radiated in the entire X-ray nova and is similar to the energy absorbed by the secondary during the same period.

The delay between the primary and the third maxima is probably associated with the inward transport, by convection, of part of the absorbed hard X-ray energy to the entire convective region. This causes the expansion which leads to the MTI. We used a full stellar model evolutionary code, for a 0.5 $M_\odot$ star, to calculate the convective overturn time scale over the star's convective region (C. Proffitt, private communication). We found the overturn time to be of order 10^7 s, which is consistent with the observed delay time. Based on this calculation, we anticipate that GRO J0422+32 may also develop a final minioutburst in early 1993.

In our scenario, the physical processes involved in the final minioutburst are somewhat different from the ones operating during the second maximum. The second maximum is merely a mass transfer episode which is a consequence of material being lifted out of the secondary's potential (by evaporation), as a result of direct heating by an X-ray blast. The last mini-outburst, on the other hand, is the consequence of a more prolonged heating phase of the secondary's external convective layers. In this case, the relatively slow expansion during the heating process is driven (at least partially) by the secondary's response to the external heating. It thus represents an intermediate case between a rapid evaporation process of the outermost material (as in the case of the second maximum) and a slow expansion of a star embedded in an external irradiation flux which is not too intense (e.g., Podsiadlowski 1991; D'Antona & Ergma 1992).

4. DISCUSSION

Using new observational data on the secondary maxima in the BHXN light curves, we proposed a *complete* scenario, which is consistent with *all* the available data. In our model, the main outburst is caused by a disk instability, while subsequent maxima result from mass transfer from the X-ray–irradiated secondary.

The following important point should be noted. In typical disk instability calculations (e.g., for dwarf nova eruptions), once the outer disk jumps down to the lower (neutral) branch in the effective-temperature/surface-density S-shaped curve, a cooling transition wave starts to propagate inward. This cooling front causes the luminosity to decay sharply. In contrast, the light curves of BHXNs exhibit a relatively long-tailed exponential decay. Furthermore, a rapidly propagating cooling front causes the disk to cool and shrink in thickness rapidly. This would have led to an exposure of the L_1 point on a faster time scale than the one we estimated above (which is based on emptying the disk mass). Apparently, X-ray novae are quite different from dwarf novae, possibly due to a much greater effect of the hard X-ray heating on the outer part of the disk (e.g., Ko & Kallman 1991). In particular, we propose that this heating significantly delays the propagation of the cooling front. Spectra taken with *HST*/FOS show no evidence for the propagation of a cooling front in the disk of XN Mus (Cheng et al. 1992). We therefore maintain that DTI models have to be modified to take into account the irradiation of the disk.

According to our proposed scenario, only after the disk loses most of its mass and the X-ray radiation drops by more than two orders of magnitude from its peak value can the disk cool via cooling transition waves as fast as conventional disk instability models predict. Observational support is provided by the fact that the final minioutburst observed in A0620−00 (and possibly in XN Mus) decays extremely fast, as would be expected from the propagation of a cooling front.

Many of the details of the proposed scenario can be tested by obtaining multiwavelength coverage of all maxima, especially during the rise to maximum (clearly not an easy observational task). Our model predicts that the main outburst always starts at the inner edge of the disk (and therefore that the rise in hard X-rays precedes the rise in soft X-rays and UV), while the subsequent maxima start at the outer edge (with the optical flux rising first). Therefore, the order of the rise times for the fluxes in different wavelength ranges should be reversed between the main outburst and the minor maxima.

We are grateful to L. Kaluzienski for providing us the X-ray light-curve data of A0620−00 and to Charles Proffitt for his assistance with calculations using his evolution code. Stimulating and informative discussions with Chris Shrader, Ken Ebisawa, Keith Horne, and Rick White are greatly appreciated.

REFERENCES

Bradt, H. V. D., & McClintock, J. E. 1983, ARA&A, 21, 13
Brandt, S., et al. 1991, in Proc. Workshop on Nova Muscae 1991, ed. S. Brandt (Lŷngbŷ: DSRI), 1
Cheng, F. H., Horne, K., Panagia, N., Shrader, C. R., Gilmozzi, R., Paresce, F., & Lund, N. 1992, ApJ, 396, 664
Chevalier, C., & Ilovaisky, S. A. 1993, IAU Circ., No. 5692
Cowley, A. 1992, ARA&A, 30, 287
D'Antona, F., & Ergma, E. 1992, preprint
Hameury, J. M., King, A. R., & Lasota, J. P. 1986, A&A, 162, 71
———. 1988, A&A, 192, 187
———. 1990, ApJ, 353, 585
Harmon, B. A., et al. 1993, in Proc. Compton Symp. (St. Louis), in press
Huang, M., & Wheeler, J. C. 1989, ApJ, 343, 229
Kaluzienski, L. J., Holt, S. S., Boldt, E. A., & Serlemitsos, P. J. 1977, ApJ, 212, 203
Kato, T., Mineshige, S., & Hirata, R. 1993, IAU Circ., No. 5704
Ko, Y.-K., & Kallman, T. R. 1991, ApJ, 374, 721
Lin, D. N. C., & Taam, R. E. 1984, in AIP Conf. Proc. 115 High Energy Transients in Astrophysics, ed. S. E. Woosley (New York: AIP), 83
Livio, M. 1992, in 22d Saas Fée Advanced Course, Interacting Binaries, ed. H. Nussbaumer, in press
Mineshige, S., Ebisawa, K., Takizawa, M., Tanaka, Y., Hayashida, K., Kitamoto, S., Miyamoto, S., & Terada, K. 1992, PASJ, 44, 117
Mineshige, S., & Wheeler, J. C. 1989, ApJ, 343, 241
Podsiadlowski, Ph. 1991, Nature, 350, 136
Ricketts, M. J., Pounds, K. A., & Turner, M. J. 1975, Nature, 257, 657
Shakura, N. L., & Sunyaev, R. A. 1973, A&A, 24, 337
Shrader, C. R., & Gonzalez-Riestra, R. 1991, in Proc. Workshop on Nova Muscae 1991, ed. S. Brandt (Lŷngbŷ: DSRI), 85
Shrader, C. R., Wagner, R. M., Starrfield, S. G., Hjellming, R. M., & Han, X. H. 1993, in Proc. Compton Symp. (St. Louis), in press
Smak, J. 1984, Acta Astron., 34, 161
Tanaka, Y., Makino, F., & Dotani, T. 1991, in Proc. Workshop on Nova Muscae 1991, ed. S. Brandt (Lŷngbŷ: DSRI), 125
Tsunemi, H., Kitamoto, S., Okamura, S., & Roussel-Dupré, D. 1989, ApJ, 337, L81
Tsunemi, H., Matsuoka, M., & Takagishi, K. 1977, ApJ, 211, L15
White, N. E. 1992, invited talk given at COSPAR Conf. (Washington, DC)
White, N. E., Kaluzienski, J. L., & Swank, J. H. 1984, in AIP Conf. Proc. 115, High Energy Transients in Astrophysics, ed. S. E. Woosley (New York: AIP), 31