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Letter to the Editor

The early optical evolution of X-ray Nova Muscae 1991

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Abstract. The optical counterpart of the new transient X-ray source, GRS 1121–68, Nova Muscae 1991, has been identified. We report here the optical position, the optical lightcurve, and two early-stage flux calibrated spectra (4000-8000Å). The available data support the binary nature of Nova Muscae 1991. Similarity with A0620-00 (hereafter V616 Mon 1975) in its early evolutionary stages lead us to consider Nova Muscae 1991 as a possible candidate black hole.

Key words: X-rays: binaries - accretion - accretion disks - black holes

1. Introduction

X-ray novae form a subclass of low mass X-ray binaries (LMXB), which are systems usually composed by a low mass late type star and an accreting compact object, a neutron star or perhaps a black hole (McClintock and Remillard 1986) . The detection of X-ray sources in such binary systems is therefore of paramount importance because they constitute the most effective observational tool to prove the existence of accreting black holes.

The X-ray transient source GRS 1121–68, was almost simultaneously detected by the All Sky X-ray Monitor aboard Ginga on 1991 January 8 (Makino et al. 1991) , and by the *Watch* all-sky X-ray camera, installed on the Soviet GRANAT satellite on January 9 (Lundt and Brandt 1991). The search for a possible optical counterpart started at the European Southern Observatory (ESO) at La Silla on January 11, but initially without success. After a more accurate position became available, the object was identified (Della Valle, Jarvis and West 1991a, 1991b) as a star of V∼ 13.5 on a IIIa–J Schmidt plate taken on January 13 with the 1-m Schmidt telescope, near the edge of the error box reported by Makino and the Ginga team (Fig. 1a) and further confirmed by X and γ observations (Sunyaev, Jourdain and Laurent 1991). Photometric and spectroscopic observations were immediately carried out with the New Technology Telescope (NTT), 2.2m and 1.5m telescopes at La Silla Observatory (Della Valle and Pakull 1991). At the position of the object, R.A. = $11^h\ 24^m\ 18^s.49$ Dec.=$-68°\ 24'\ 01''.7$ (1950.0), the progenitor is barely visible on the best ESO (R) Schmidt plates (1984) having a magnitude close to the R$\simeq$ 20 (Fig 1b).

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2. The Pre-Nova

A total of twelve photographic plates which cover the area around Nova Muscae 1991 were available at ESO and have been studied; they are listed in Table 1 in chronological order:

Table 1: Available plate material

Plate Id.	Date (UT)	Exp.	Emul. + Filter
ESO 1270	1976 Feb. 02.30	60	IIa-O + GG385(B)
SRC 2172	1976 Apr. 03.52	50	IIIa-J + GG395(J)
ESO 1536	1976 Jun. 20.98	40	IIIa-F + RG630(R)
SRC 4168	1978 Apr. 18.50	90	IV-N + RG715(I)
SRC 4169	1978 Apr. 18.54	10	IIIa-F + RG610(R)
ESO 5476	1984 Jan. 29.31	120	IIIa-F + RG630(R)
ESO 5539	1984 Feb. 22.24	120	IIIa-F + RG630(R)
GPO 14403	1991 Jan. 11.29	10	IIa-O (no filter)(B)
GPO 14404	1991 Jan. 11.33	10	IIa-O (no filter)(B)
ESO 8955	1991 Jan. 13.26	45	IIa-O + GG385(B)
ESO 8959	1991 Jan. 14.27	90	IIIa-J + GG385(B)
ESO 8965	1991 Jan. 15.33	60	IIa-O + GG385(B)

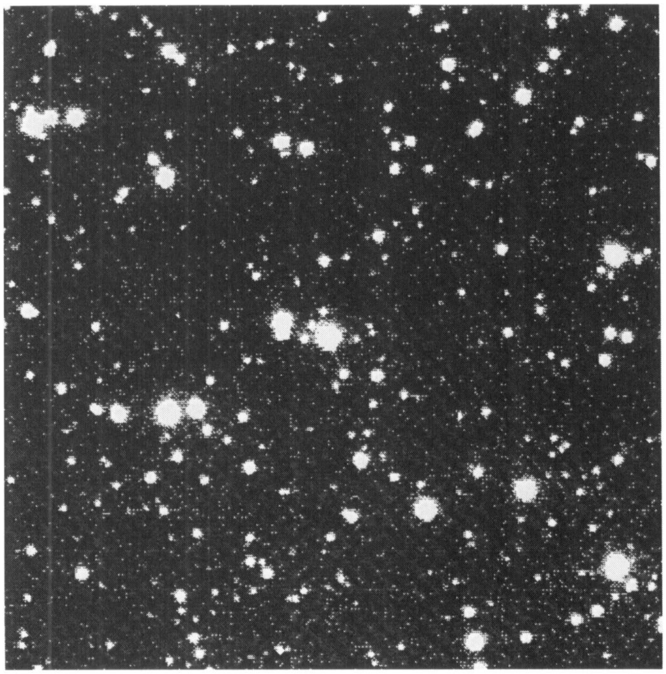
ESO = ESO 1m Schmidt telescope; SRC = UK 48-inch Schmidt telescope; GPO = ESO 40 cm double astrograph. Exposure in min.

A faint, star-like object is seen on the deepest, pre-outburst plates at the approximate position of the nova. In order to verify the identity, accurate astrometric positions of the presumed pre-nova were measured on the the deepest blue plate (SRC 2172) and on a combined R(290 min) frame, and then compared with the position of the nova as measured in a 5 sec R-frame, obtained at the NTT on 1991 Jan. 15.3.

Twelve secondary astrometric standards within 1 arcmin of the nova position were measured on a deep red plate (ESO 5476), relative to twenty-three primary standards from the PPM Catalogue (Röser and Bastian 1990); which gave a position for the nova with r.m.s. values of $\sigma(\alpha \cdot cos\delta)$ = 0.22 and $\sigma(\delta)$ = 0.17 arcsec. The interpolated positions of the pre-nova, nova and the differences (arcsec) are given in Table 2a and Table 2b.

Table 2a: Astrometric positions

Object	R.A.(1950)	Decl. (1950)
Prenova (B)	$11^h\ 24^m\ 18^s.51$	$-68°\ 24'\ 01''.9$
Prenova (R)	$11^h\ 24^m\ 18^s.52$	$-68°\ 24'\ 02''.2$
Nova (R)	$11^h\ 24^m\ 18^s.49$	$-68°\ 24'\ 01''.7$



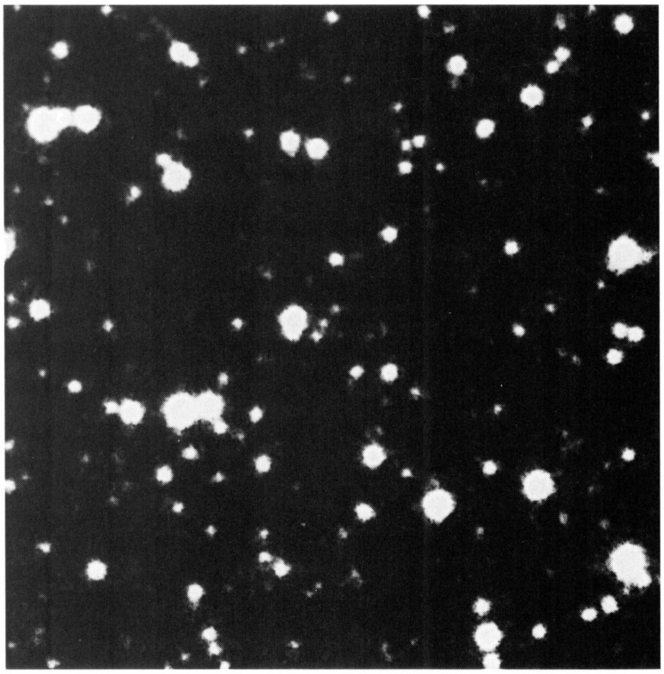


Fig. 1a. Nova Muscae 1991 during its flare up in early January 1991 in the southern constellation of Musca. The CCD frame was secured on 15.3 January 1991, (seeing 0.9 arcsec); with the ESO New Technology Telescope (5 sec exposure in R). The nova is the bright object at the centre. Fig. 1b. Reproduction of an earlier red-sensitive ESO Schmidt plate (120 min exposure on IIIa-F + RG630; 29 January 1976). The pre-nova is faintly visible.

Table 2b: Astrometric differences

Difference (″)	$\Delta\alpha \cdot cos\delta$	$\Delta\delta$
Nova – Prenova(B)	−0.15	+0.19
Nova – Prenova(R)	−0.20	+0.49
Prenova(B) – (R)	−0.05	+0.30

The positions agree to within the astrometric uncertainties, confirming the identification of the pre-nova of Nova Muscae 1991.

Pre-nova magnitudes were measured from these plates, all scanned with a PDS microdensitometer. The resultant magnitudes are listed in Table 3 and were interpolated from secondary photometric standards established in two CCD frames obtained with the ESO NTT (R, 5 sec; 13.4-19.7 mag) and 2.2m (B, 1 min; 13.0-20.2 mag) telescopes. Because of the faintness of the pre-nova on the red plates, the four plates were co-added to produce a combined "R(290 min)" frame. The pre-nova was not visible on the SRC(I) film.

Table 3a: Pre-Nova Photographic Magnitudes

Plate Id.	B	$\pm\sigma_B$	R	$\pm\sigma_R$
ESO 1270	~ 21			
SRC 2172	20.9	0.2		
ESO 1536			> 19	
SRC 4169			> 19	
ESO 5476			19.5	0.2
ESO 5539			19.6	0.2
R(290min)			19.3	0.1
Mean	20.9	0.2	19.4	0.1

The nova was apparently still rising on Jan 11.29 and probably levelled off at B = 13.5 before Jan 12.3.

Table 3b: Nova Photographic Magnitudes

Plate Id.	B	σ_B
GPO 14403	14.04	0.05
GPO 14404	13.83	0.05
ESO 8955	13.74	0.08
ESO 8959	13.94	0.15
ESO 8965	13.70	0.05

3. The Observations

The striking feature of the photometric evolution of Nova Muscae 1991 was the sudden increase of brightness (about 8 mags) which led to a classification of the object, in the first instance, as a classical nova. The epoch of maximum light may be inferred by examining the light curve shown in Fig. 2. It probably took place between January 11 (JD=2448268) and January 12 (2448269) at a magnitude V$\simeq$ 13.3 and B$\simeq$13.5. The optical lightcurve of Nova Muscae 1991 mimics well the optical evolution of of V616 Mon 1975 (Lloyd, Noble and Penston 1991) regarding the amplitude of the outburst, the decay rate (~ 0.024 mag day^{-1}) computed over the first 45 days past maximum and the variations in brightness ($\simeq$ 0.2 mag) on a time scale of ~ 1 day, observed in the three photometric bands. This decline appears slower than that shown by Cen X-4, which faded by two magnitudes in the first 30 days past maximum.

The spectrum (Fig. 3), obtained with the NTT telescope on January 15 (resolution ~ 10Å) does not resemble that of a classical nova at an early stage.

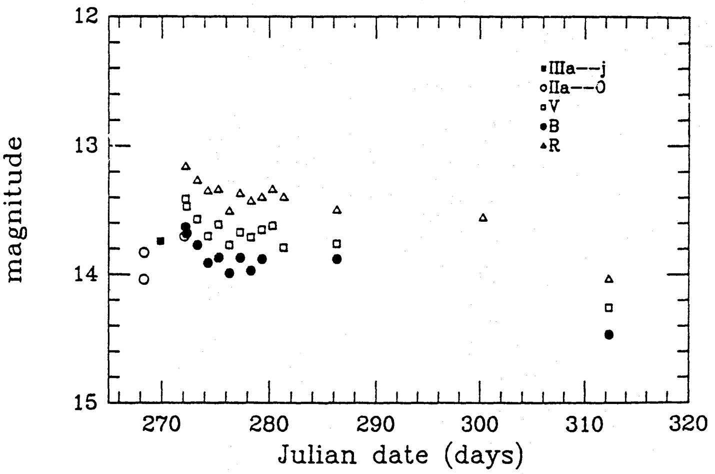


Fig. 2. Light curve of Nova Muscae 1991 during the early stages after outburst in the B,V, and R colors.

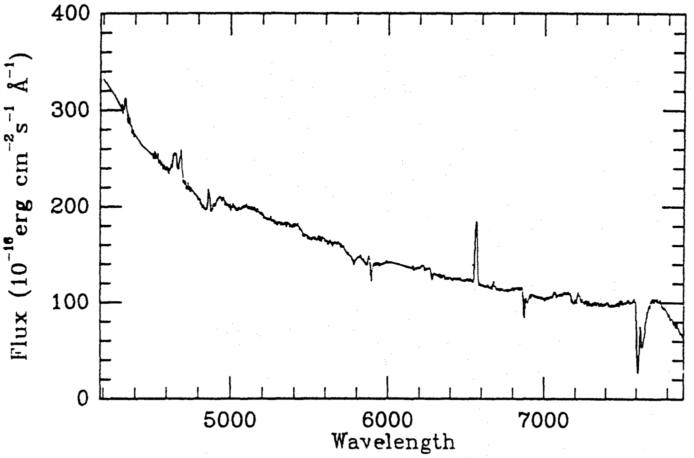


Fig. 3. Spectrum of Nova Muscae 1991 in the range 4000-8000Å (resolution ~ 10Å), obtained on January 15.3 UT at NTT.

We note the complete absence of FeII, NaI, OI and Balmer emission lines coupled with *P Cyg* profiles which normally predominate in the ***pre-maximum*** and ***principal*** spectra of novae at early stages (Payne-Gaposchkin 1957). Indeed the spectrum of Nova Muscae 1991 is dominated by Balmer, He and N emission lines (see Tab. 4) superimposed on a blue continuum. Comparison with other well studied X-ray novae, shows that this spectrum closely resembles that of the optical counterpart of Centaurus X-4 (Canizares, McClintock, and Grindlay 1980) and V616 Mon 1975 (Whelan et al. 1977, Boley et al. 1976, Ciatti et al. 1977). Fig. 4 shows that the main spectroscopic features visible in the spectrum are: a) The *NIII blend* at 4640Å (EW=3.5Å). The NIII emission is normally attributed to the X-ray heating driving the Bowen fluorescence process (McClintock, Canizares and Tarter 1975), but in the present case it appears broadened by the OII and CIII ions. On the red wing we observe the 4686Å HeII line (EW=2.4Å). b) The *Balmer lines* are seen in emission filling in shallow absorptions. Values for the Balmer decrement as deduced from the table are: Hα/H$\beta \simeq 4$ and H$\gamma/H\beta \simeq 0.5$. c) The main ***interstellar features*** are the interstellar bands at 5780, 5778 and 5797Å, which are also blended (EW=0.9Å); the unresolved Na-D lines (EW=1.4Å); and the blend due to the absorption lines 6269+6282Å (EW=0.5Å).

Table 4: Emission Lines

Line	λ(Å)	Flux (10^{-16} erg s^{-1} cm^{-2})
Hγ	4340	150
NIII	4640	800
He II	4686	550
Hβ	4861	300
He I	5876	100
Hα	6563	1200
HeI + HeII	6678-6683	81
He I	7068	85
NII	7220	70

A later spectrum (~ 3 months past maximum) still showed a blue continuum, but the emission features were dramatically weaker (see Fig. 5).

4. Reddening and Distance

We can estimate the amount of the color excess in a number of different ways. A preliminary indication comes from the strength of the interstellar absorption lines of NaD. Using the empirical relation recently revised by Barbon et al. (1990) between the color excess and the EW of the NaD lines, we estimate from an EW of 1.4Å, a color excess of E(B−V)=0.3. This is consistent both with the IUE measurement by Gonzales et al. (1991), $E(B-V) = 0.20 \pm 0.05$, rising from the dust absorption at 2200Å and with E(B−V)=0.35 that we have derived from the strength of the absorption bands at 5778, 5780 and 5797Å(Herbig 1975). In the following we shall adopt $\langle E(B-V)\rangle = 0.30 \pm 0.10$.

The estimate of the distance of Nova Muscae is quite uncertain. Since Nova Muscae 1991 is not a classical nova, the relation between the absolute magnitude at maximum and the rate of decline (MMRD), well established for galactic novae, cannot be successfully applied. The MMRD relation derived by Capaccioli et al. (1989) for galactic novae, combined with the parameter values derived above (V_{max} = 13.3, E(B−V)=0.30, rate of decline V_d=0.024 mag day^{-1}), yields a distance of d$\simeq$ 60 kpc, which is highly unlikely. Alternatively, an estimate of the distance can be inferred from the linear relation between the EW of the NaD lines and the distance (Charles et al. 1988). In this case we get the more reasonable value of d $\simeq$ 1.4 kpc. Combining this distance with the measurements of integrated flux between 1200 and 3200Å (1.1 $\times 10^{-10}$ erg cm^{-2} s^{-1}) (Gonzales et al. 1991), between 4000 and 8000Å (~ 0.7 × 10^{-10} erg cm^{-2} s^{-1}) (this paper), and between 35–150 keV (~ 2 × 10^{-8} erg cm^{-2} s^{-1}) (Sunyaev, Jourdain and Laurent 1991), we get an UV+optical flux at maximum of $F_{\rm opt}^{\rm max} \sim 4 \times 10^{34}$ erg s^{-1}, a X-flux of $F_{\rm x}^{\rm max} \sim 10^{37}$ erg s^{-1}, and a $F_x/F_{\rm opt} \geq 1000$ i.e. typical values for low mass X-ray binaries stars (LMXB) in outburst (Van Paradijs and Verbunt 1984).

5. Discussion

Even though the photometric evolution of Nova Muscae 1991 resembles, in some regards, that of a classical nova, both the features exhibited by the spectrum as well as the amount of the energy realized during the outburst fit well the characteristics of the optical counterparts of X-ray sources like Sco X-1,

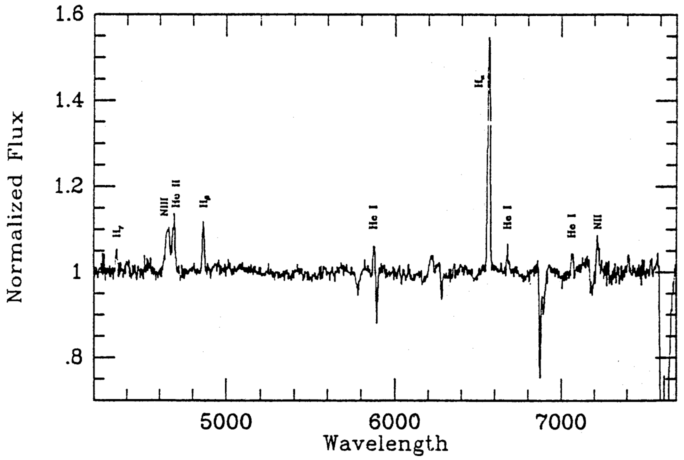


Fig. 4. Continuum normalized spectrum of Nova Muscae 1991 obtained on January 15.3 UT at NTT.

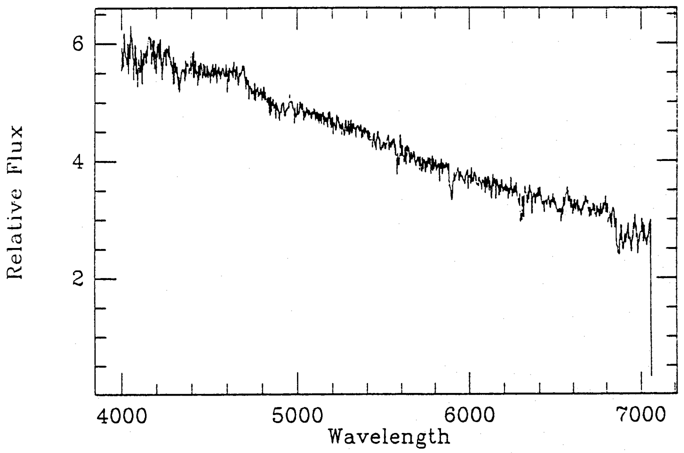


Fig. 5. Spectrum of Nova Muscae 1991 in the range 4000–7000Å obtained on May 19 at the ESO 3.6m telescope under non-photometric conditions.

Cen X-4, V616 and Mon 1975. With d=1.4 kpc and B=19.8 (magnitude at minimum after reddening correction), we derive $M_B \simeq +9.2$, for the progenitor. This is consistent with the absolute magnitude of a low mass main sequence star of spectral type ~ K5–M0 (Allen 1976). According to current understanding, these late spectral type stars have been recognized as the most probable companions of the degenerate stars in the LMXB systems (Van Paradijs and Verbunt 1984).

These observational facts support the idea that the energy source during the paroxysm has been supplied by the gravitational potential energy released during the accretion from the disc onto a compact companion. This energetic production, according to current models, can be triggered by an accretion rate from the disk onto the compact star smaller than the mass transfer rate from the secondary to the disk (the so-called *disk-instability* model) and/or through sudden increase of mass transfer rate from the secondary onto the accreting object (the so-called *mass transfer instability* model). Finally the large amount of energy released in the X-ray band, which is at least 10^3- 10^4 times larger than that emitted by a normal cataclysmic variable, suggests that the compact object which has accreted material from the K-M dwarf, is probably a neutron star but does not exclude a black hole (McClintock and Remillard 1986; White 1989).

The binary nature of Nova Muscae should become directly detectable in the next months, when it is expected that the star returns again to minimum light.

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