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THE OPTICAL COUNTERPART OF GX 339−4, A POSSIBLE BLACK HOLE X-RAY SOURCE

JONATHAN E. GRINDLAY[1]
Harvard-Smithsonian Center for Astrophysics
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ABSTRACT

Optical studies of the galactic X-ray source GX 339−4 (4U 1658−48), which led to its recent identification as reported by Doxsey *et al.*, are presented here. Reddening and distance estimates are given as well as evidence for optical variability on differing time scales. The emission-line spectra and *UBV* photometry suggest that GX 339−4 may be at ~8 kpc and have a main-sequence B star binary companion. Both the optical spectrum and optical/X-ray luminosity ratio for GX 339−4 may be similar to Cir X-1.

Subject headings: black holes — X-rays: sources

I. INTRODUCTION

The precise positions (~20″) for X-ray sources recently obtained by the *SAS 3* and *HEAO* A-3 groups have enabled many successful searches for optical counterparts, even in crowded fields near the galactic plane. Doxsey *et al.* (1979) have identified the optical counterparts of two highly variable galactic X-ray sources, GX 339−4 and MXB 1659−29, using *HEAO* A-3 X-ray positions and our optical observations of these fields. In this *Letter*, we shall report the optical observations of the GX 339−4 field in more detail than was possible in Doxsey *et al.*, and additional optical data are presented which may further constrain models.

The source GX 399−4 = 4U 1658−48 is an especially interesting galactic X-ray source. It is the third (after Cyg X-1 and Cir X-1) candidate black hole source, since it also shows large intensity fluctuations on time scales ~40 ms (Samimi *et al.* 1979) as well as possibly a two-component (soft and hard) spectrum with high and low states like Cyg X-1 and Cir X-1 (Doxsey *et al.* 1979). We shall show that in its optical properties (i.e., strong Hα emission, comparable L_x/L_{op}), it is also similar to Cir X-1.

II. OPTICAL SPECTRUM AND VARIABILITY OF GX 339−4

The optical counterpart for this source was discovered during our spectrophotometric survey of stars in the *HEAO* A-3 error box (see Doxsey *et al.* 1979 for a finding chart). The actual identification (at the telescope) was made on the basis of strong Hα emission. Spectra were obtained using the Ritchey-Chrétien spectrograph and SIT vidicon camera on the 4 m telescope at Cerro Tololo Inter-American Observatory (CTIO) on 1978 May 30 and 31. Grating 181 was used (with 300 lines per mm) and tilt at 61°.5 for response from λλ4200 to 7000 and resolution ~20 Å. Spectra were also obtained of three other stars within ~1′ of GX 339−4 for a determination of reddening. Absolute flux calibrations were obtained from spectra of several white dwarfs (Wolf 485 A, L930-80), and the initial reduction of the spectra was done using the CTIO facilities in La Serena. Photometry (*UBV*) of the candidate was also conducted on 1978 June 1 using the 1.5 m telescope at CTIO.

The GX 339−4 spectra on both nights (Figs. 1*a*, 1*b*) showed strong emission at Hα, He II (λ4686), and C III–N III (λλ4640–4650) with equivalent widths of 4.4–5.8 ± 0.5, 2.5 ± 0.5, and 2 ± 1 Å, respectively. The Hα flux decreased from equivalent width 5.8 ± 0.5 Å on May 30 to 4.4 ± 0.4 Å on May 31. Hβ emission was marginally detected on May 30 with equivalent width 1.0 ± 0.3 Å but was not detected (0.4 ± 0.4 Å) on May 31. Thus the spectra are consistent with a constant Hα/Hβ emission ratio of ~6 ± 2. Both spectra also show strong Na D absorption, presumably due to interstellar extinction (see discussion below). The apparent absorption feature at λ5577 (in Fig. 1*a*) is due to an imperfect subtraction of the strong night-sky emission at this wavelength. Other (interstellar) absorption-line features will be discussed below.

Comparison of the two spectra shows that the continuum spectra are essentially identical on both nights at wavelengths below ~5500 Å, but that there is a small enhancement at longer wavelengths on May 31 even though the Hα emission has decreased. Indeed, integration of the spectra over the *V* band (with the passband efficiencies given by Allen 1973) gives a ~0.2 mag brightening in *V* as shown in Table 1. The *B* mag also given in the table are derived (for the May 30–31 spectral data only) from the apparent flux detected at λ4350 (Allen 1973).

A systematic brightening by ~0.2–0.3 mag of the GX 339−4 counterpart over the 3 day span of our observations is indicated by a comparison of the *UBV* photometry data of June 1 with the spectrophotometry

[1] Visiting Astronomer, Cerro Tololo Inter-American Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

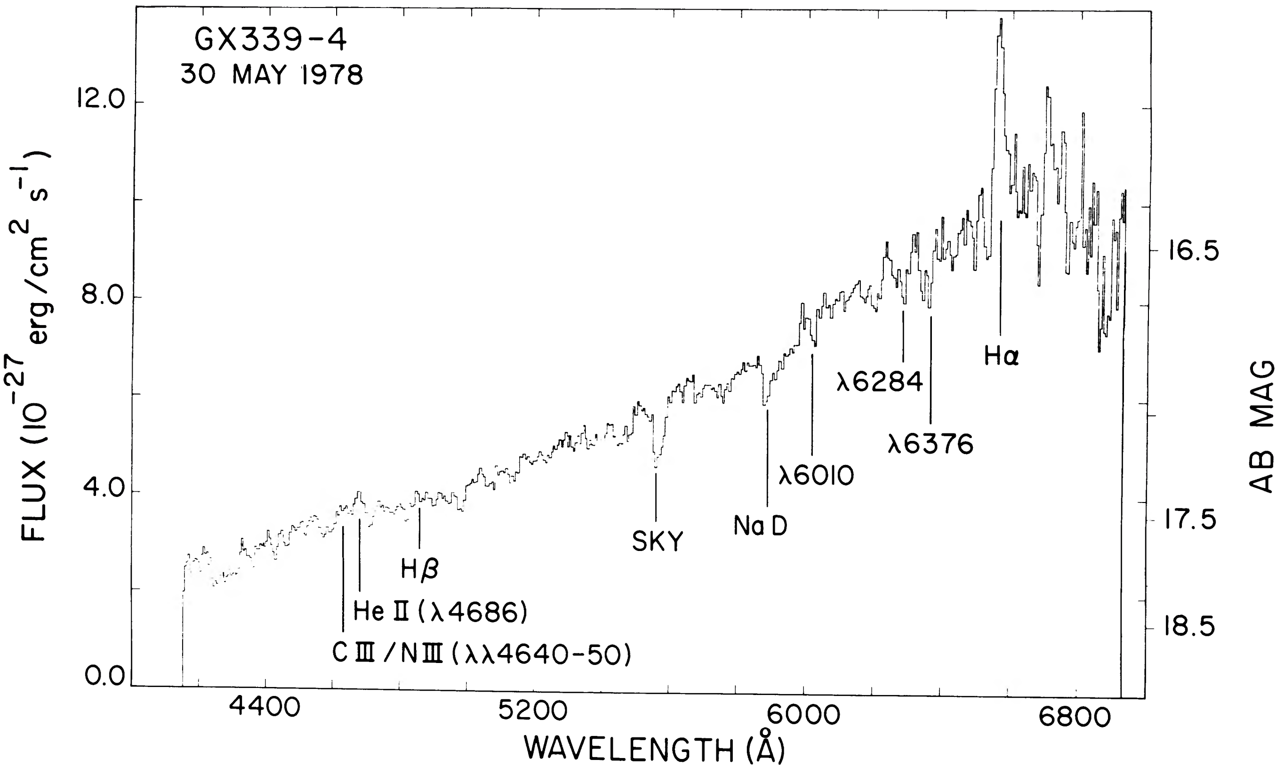

FIG. 1a

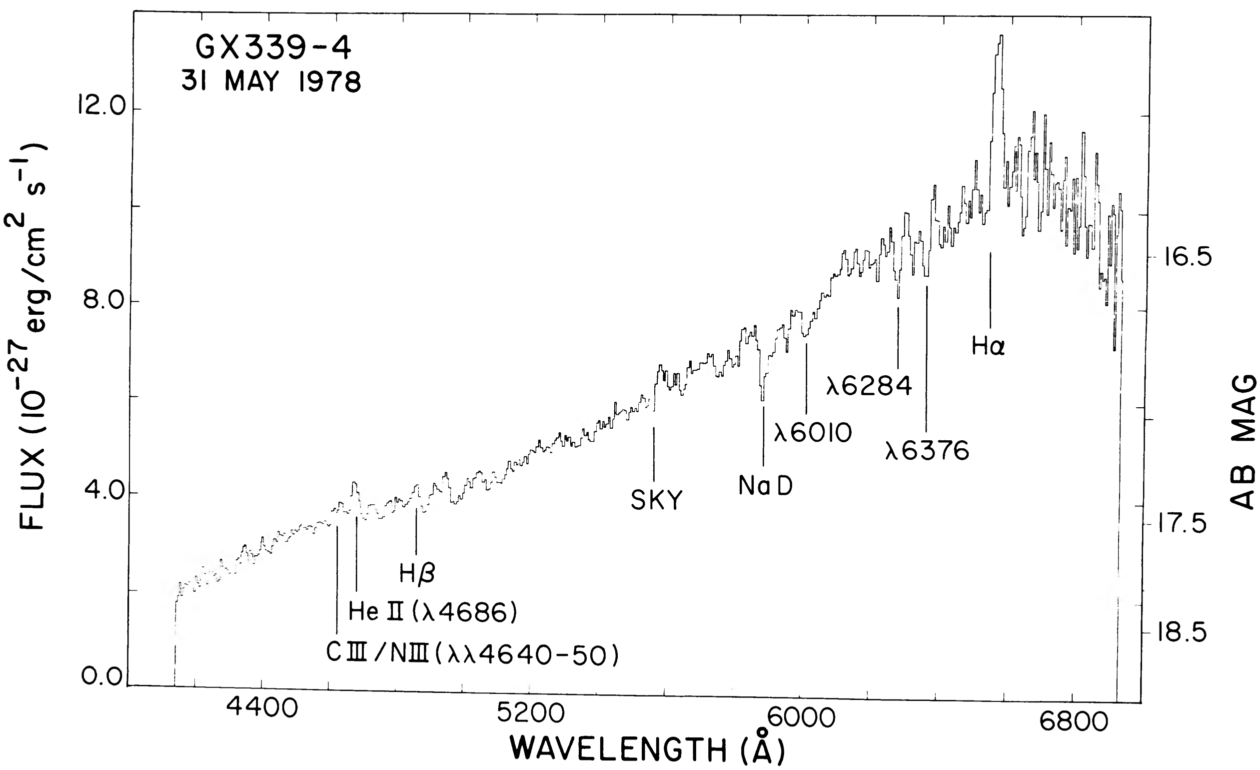

FIG. 1b

FIG. 1.—Spectra of the optical counterpart of GX 339−4 (4U 1658−48) recorded with the 4 m telescope and Ritchey-Chrétien spectrograph and SIT vidicon camera at CTIO on (*a*) May 30 and (*b*) May 31. Prominent emission and absorption lines are marked. The absorption lines are consistent with an interstellar extinction of $E(B-V) \approx 1.2$ mag.

TABLE 1

1978 PHOTOMETRY OF GX 399−4 = 4U 1658−48

	V	$(B-V)$	$(U-B)$
Spectrophotometry (4 m tel.):[a]			
May 30, 05:20 UT	17.15	0.85	...
May 31, 06:15 UT	17.00	0.95	...
Photometry (1.5 m tel.):[b]			
Jun 1, 05:30 UT	16.73	0.88	−0.21
Jun 1, 05:39 UT	16.68	0.84	−0.27
Jun 1, 05:50 UT	16.67	0.88	−0.25
Jun 1, 06:15 UT	16.64	0.82	−0.17
Jun 1, 06:26 UT	16.64	0.96	−0.17

[a] Errors estimated to be ±0.15 mag.
[b] Errors estimated to be ±0.05 mag.

of May 30–31. The photometry data are also summarized in Table 1, where the errors on all individual magnitude measures are estimated to be ±0.05 mag. Although variability over the 3 day period is indicated, the source is consistent with a constant optical flux during the ∼1.5 hours of photometry on June 1.

Given this evidence for variability of the GX 339−4 optical counterpart (and also that reported in the "pre-discovery" observations of Penston *et al.* 1975), we have measured a historical light curve (ca. 1930–1950) for GX 339−4 using the archived Harvard plate collection. The result is shown in Figure 2, where the photographic magnitude is plotted for all plates in the HCO archive where the star was clearly visible. The magnitudes are visual estimates made by

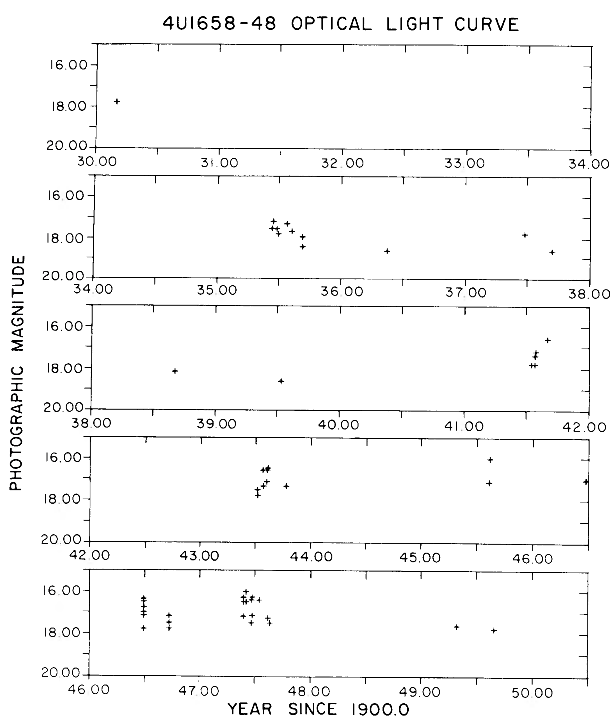

FIG. 2.—Historical light curve for the optical counterpart of GX 339−4 as measured on HCO archive plates. Magnitude errors are estimated to be ±0.2 mag.

interpolating between a series of six to 10 control stars, whose magnitudes were in turn measured from the ESO B survey plate. Typical errors are estimated to be ±0.2 mag. (The GX 339−4 optical counterpart has an apparent B magnitude on the ESO B plate of only 18.3, or ∼0.7 mag fainter than during our observations.) It is obvious that GX 339−4 is an erratic variable, with changes of ∼1 mag on time scales of hours possible. We find no obvious long-term trends in the variability. No significant periods were found in a periodicity search (with $P \geq 3$ days) performed on both the entire data set and individual years of relatively dense coverage. However, the relatively few data points limit the sensitivity of such a search to periodic amplitudes $\gtrsim 30\%$. Obviously more monitoring is needed, particularly to search for short (≤ 3 day) periods.

III. REDDENING ESTIMATES FOR THE GX 339−4 FIELD

Spectra of three stars within ∼1′ of GX 339−4 were obtained as part of an effort to determine local reddening. The stars observed may be found on the finding chart (Fig. 1 of Doxsey *et al.*) at offsets (from star V = GX 339−4) of: ∼10″ SE (star 2), ∼75″ SW (star 7), and ∼8″ NE (star 8). The SIT spectra were compared with the spectra and classification given in the *Atlas for Objective Prism Spectra* by Seitter (1970). Two of the field stars were thus identified as K0–K2 with luminosity classes IV–V, whereas the third star is most likely a G5 III giant. Integration of our SIT spectra with the standard UBV filter response functions (Allen 1973) then enabled estimates (to within ∼0.1–0.2 mag) of the observed values for V and $(B - V)$ for each star. Comparison with the corresponding unreddened values of $(B - V)$ for each spectral type then yielded $E(B - V)$ and thus the total extinction $A_v \approx 3E(B - V)$ as well as the distance d. The results are summarized in Table 2 and indicate that $A_v/d \approx 2$ mag kpc^{-1} for the GX 339−4 field. This compares well with the value found for this region in the general reddening study of FitzGerald (1968).

The estimated values of A_v given in Table 2 for the GX 339−4 field stars are consistent with the strength of several interstellar absorption features evident in their spectra. Most prominent of these are the Na D lines as well as features at $\lambda \sim 6010$ Å, ∼6284 Å, and 6376 Å in addition to the diffuse 4430 Å band. The correlations between absorption depth or equivalent width in these features and the reddening $E(B - V)$ have been studied by Bromage and Nandy (1973). Using these correlations and the strength of these absorption features in our SIT spectra, we find good agreement with the values of $E(B - V)$ given in Table 2.

IV. CLASSIFICATION AND DISTANCE ESTIMATES

The spectra of the GX 339−4 optical counterpart (Fig. 1) show strong Na D absorption as well as

TABLE 2

REDDENING STUDIES OF GX 339−4 FIELD

		Integration of SIT Spectra (mag)				
Star	Classification	V	$(B-V)$	$E(B-V)$	d (kpc)	A_v/d (mag kpc^{-1})
Star 2	K0 IV	14.0	2.0	0.5	0.7	2.0
Star 7	G5 III	12.6	1.5	0.7	1.0	2.1
Star 8	K2 IV–V	17.5	1.8	0.9	0.6–2	1–4

evidence for interstellar absorption at $\lambda \sim 5775$–5795, 6010, 6176, 6284, and 6376 Å. The diffuse λ4430 band may be masked by the decreased sensitivity and uncertain continuum shape at λλ4200–4400. From Bromage and Nandy (1973), the Na D lines alone, with equivalent width 2.2 ± 0.4 Å, would predict $E(B-V) \approx 1.25 \pm 0.25$ if they are entirely due to interstellar absorption. The other interstellar lines are weaker (with equivalent widths at 5775–5795, 6010, and 6284 Å of ~1.5 Å, ~0.3 Å, and ~1.2 Å, respectively) and less well determined in our spectra but they are all consistent with $E(B-V) \approx 1.2$. Thus the total extinction toward GX 339−4 is probably $A_v \approx 3E(B-V) = 3.75 \pm 0.75$ mag.

From our *UBV* photometry (Table 1) and the range for $A_v \approx 3$–4.5 mag, we may now estimate the spectral types and distance for the GX 339−4 optical counterpart. Good agreement with the broad-band colors is obtained if the counterpart is a B0 V–B2 V star at ~8–25 kpc with extinction $A_v \approx 3.5$–4 mag. The B2 V classification is preferred, since at ~8 kpc the source is already at $z \approx 500$ pc from the galactic plane; still earlier spectral types, which would be at larger distances, would be even less likely, since they would imply even larger z-values. Note that even $z \sim 500$ pc may imply a large velocity given the z-distribution of normal B stars with scale height $z_0 \lesssim 100$ pc (Blaauw 1965). Note also that the distance (~8 kpc) and absorption (3.5 mag) estimates are consistent with our reddening study result of $A_v/d \sim 2$ mag kpc^{-1}, since the line-of-sight path breaks out of the ~100 pc thick (Allen 1973) dust layer at ~1.5 kpc.

The spectrum of a normal B2 V star would be dominated by strong absorption lines in the hydrogen Balmer series as well as He I absorption lines. Instead, we see (cf. Fig. 1) strong Balmer emission and He II emission and no absorption lines except those due to interstellar matter. As discussed below, these emission lines probably arise from X-ray heating of the stellar atmosphere of the B2 V binary companion. Note that although Balmer emission alone (e.g., Hα) could imply a Be classification, the He II emission would be most unusual for a Be star. Our spectral sensitivity falls off rapidly near Hγ (λ4340) and thus our limits for the equivalent width of Hγ absorption, or for an Hγ index—which is a good discriminator for a B1–5 V classification (O'Connell 1973)—are not restrictive.

V. DISCUSSION AND CONCLUSIONS

Our results indicate that GX 339−4 may have a main-sequence B star binary companion with moderately strong effects of X-ray heating (e.g., Balmer lines, He II, C III–N III lines in emission) as in other galactic X-ray source counterparts (McClintock, Canizares, and Tarter 1975). This interpretation is supported primarily by the measured interstellar absorption lines in the GX 339−4 spectrum which indicates (with the *UBV* colors) a reddening ($A_v \sim 3.5$ mag) and distance ($d \sim 8$ kpc) appropriate to an early–mid B star on the main sequence. The system would then have an X-ray luminosity $L_x \sim 3 \times 10^{37}$ ergs s^{-1} (for a typical X-ray flux of ~150 UFU) and a ratio $L_x/L_{op} \sim 3$, which is similar to that deduced for Cir X-1 (Whelan *et al.* 1977). This similarity is especially interesting, since the X-ray source behavior (~50 ms fluctuations) and optical spectrum (strong and variable Hα emission) are also very similar.

We cannot exclude the possibility that GX 339−4 is totally dominated by X-ray heating and is as close as ~2–3 kpc (minimum for $A_v \sim 3$–4 mag) with absolute magnitude $M_v \sim 1$ and $L_x/L_{op} \approx 750$. This would then be similar to the optical counterparts of X-ray bursters (McClintock *et al.* 1977; Doxsey *et al.* 1979). However, the strong Balmer emission and quiescent source optical variability (or flickering) is not seen in burst sources (Grindlay *et al.* 1978; Canizares, McClintock, and Grindlay 1979) as it is for GX 339−4, and this may be an important discriminator. Clearly, the best test for whether GX 339−4 has a main-sequence stellar companion or more closely resembles the bursters is to measure its optical spectrum over a range of apparent magnitudes (see the optical variability of Fig. 2), and to search for correlated X-ray intensity changes. If the He II emission lines decrease and appear in absorption (as in a normal B2 V star) at low X-ray and optical flux levels, then the B star identification will be supported. It is interesting to note that our optical observations were recorded when the X-ray flux (particularly the soft component) may have been increasing, since the *SAS 3* observations on 1978 June 21 (Li, Clark, and Rappaport 1978) showed the flux had increased by a factor of ~3 from May 25 and a factor of +30 from earlier *HEAO 1* observations on 1978 March 12 (Samimi *et al.* 1979).

Continuous monitoring and emission-line velocity measurements are needed to search for periodic effects. Whereas the similarities to Cir X-1 would suggest a relatively long ($P \sim 10$ day) binary period, the probable optical flickering and large X-ray heating would suggest a relatively close separation ($P \sim 2$ day) binary. Establishing the binary nature of GX 339−4 at optical or X-ray energies could constrain the X-ray source mass and test the black hole hypothesis.

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JONATHAN E. GRINDLAY: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138