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SIMULTANEOUS X-RAY AND OPTICAL OBSERVATIONS OF THE 7.7 SECOND X-RAY PULSAR 4U 1626−67[1]

J. E. McCLINTOCK,[2] C. R. CANIZARES,[2] AND F. K. LI
Department of Physics and Center for Space Research, Massachusetts Institute of Technology

AND

J. E. GRINDLAY[2]
Harvard-Smithsonian Center for Astrophysics
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ABSTRACT

Simultaneous X-ray and optical observations of the 7.7 s X-ray pulsar 4U 1626−67, obtained during 1978 May 29–31, reveal the presence of (1) intense, correlated optical and X-ray flares and (2) 7.7 s optical pulsations which agree in phase with the 1–3 keV X-ray pulsations to within 0.5 s (2 σ) and which agree in period to within 0.001 s (1 σ). From these data we conclude that a substantial fraction (a minimum of 8%) and possibly all of the optical emission is produced from within ~0.5 lt-sec or 1.5×10^{10} cm of the neutron star. Furthermore, the data rule out the possibility that this optical emission comes from the X-ray heated surface of a degenerate or nondegenerate dwarf companion. It most likely comes from an accretion disk.
Subject headings:— stars: accretion — X-rays: sources

I. INTRODUCTION

The 7.7 s X-ray pulsar 4U 1626−67 is remarkable for several reasons. First, it is unlike any of the other 13 optically identified X-ray pulsars, 11 of which are luminous OB stars (Bradt, Doxsey, and Jernigan 1978). The optical counterpart of 4U 1626−67 is extremely faint and blue and its spectrum is devoid of any normal stellar features. It is similar to the ~20 known counterparts of the Sco X-1–like sources (Margon 1978) which are old, low-mass systems that do not pulse. Second, X-ray timing measurements by Rappaport *et al.* (1977), Joss, Avni, and Rappaport (1978), and Pravdo *et al.* (1979) have failed to reveal any evidence of binary motion and have placed very strong limits on the projected orbital radius of the X-ray star: $a_x \sin i \lesssim 0.2$ lt-sec for 1 hour < $P_{\rm orb}$ < 20 days. Third, 4U 1626−67 has a unique and intense X-ray flaring behavior with a quasi period of ~20 minutes (Joss, Avni, and Rappaport 1978; § III of this *Letter*). Fourth, the optical modulation (Ilovaisky, Motch, and Chevalier 1978) is an order of magnitude greater than for Her X-1, the only other confirmed X-ray/optical pulsar.

II. OBSERVATIONS

Photoelectric monitoring of 4U 1626−67 was performed during 1978 May 30 (one day after third quarter moon) and May 31 UT using the CTIO 1.5 m telescope and a very broad bandpass, 3100–5500 Å (FWHM). The average source count rate was ~90 counts s^{-1} and the sky count rate was ~180–520 counts s^{-1} depending on the phase and the position of the Moon. During the first night, May 30.22–May 30.42 UT, the optical data were recorded in 50 s integrations and observations of 4U 1626−67 were alternated with observations of the sky and a nearby reference star (see Fig. 1*a*). During the second night, May 31.10–31.25 UT, 4U 1626−67 was monitored continuously (see Fig. 1*b*). The instrumentation and observing techniques are identical to those described by Grindlay *et al.* (1978).

Continuous, pointed-mode X-ray observations of 4U 1626−67 were made during the interval May 29.0–31.3 UT using the *SAS 3* satellite (see Rappaport *et al.* 1977 for a description of the instrumentation and observing techniques). We used production data in our analysis which contain the absolute time to an accuracy of ±5 ms of UT (McClintock *et al.* 1979). Unfortunately, during the simultaneous observations on May 30 and 31 UT, there were large data losses which were due to the propagation of the VHF telemetry signal through disturbances in the ionosphere (see Fig. 1).

III. RESULTS

a) X-ray and Optical Flares

Correlated X-ray and optical flaring behavior is evident in the two nights of data shown in Figure 1*a*, *b*. Both the optical and X-ray flares have durations of ~5–10 minutes. A blowup of the prominent flare in Figure 1*b* is shown in Figure 2. A plot of the optical intensity *versus* the simultaneous 1–12 keV X-ray

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intensity for the data obtained on May 30 (Fig. 1*a*) and May 31 (Fig. 2) is shown in Figure 3. On both nights the X-ray intensity varied by a factor of ~3–4 and the optical intensity by a factor of ~1.5. The data show that a significant change in the relationship between optical intensity and X-ray intensity occurred in the source in one day. The smooth curves in Figure 3 are power-law fits to the data: $I_{opt} = 308\ I_x^{0.27}$ for May 30 (dots) and $I_{opt} = 269\ I_x^{0.36}$ for May 31 (crosses). For a discussion of the physical basis of the power-law relationship and additional data see Grindlay *et al.* (1978) and references therein. A power-law exponent, α, was also derived for the relationship between the soft 1–3 keV X-ray flux and the optical flux for the flare event shown in Figure 2: α (1–3 keV) = 0.21. It is significantly less than the one found above for the same time interval, α (1–12 keV) = 0.36, owing to the greater flare intensity at low X-ray energies (see Fig. 1 in Joss, Avni, and Rappaport 1978).

b) 7.7 Second Pulsations

X-ray data for the interval 1978 May 29.4–30.8 UT were folded modulo the best-fit pulse period, which was determined by the iterative procedure described in Rappaport *et al.* (1977) and references therein. The resultant pulse profiles are shown in Figure 4 for five energy intervals between 1.2 and 39 keV. They are remarkably similar to the ones observed 14 months earlier by Rappaport *et al.* (1977). We find for the heliocentric X-ray pulse period P_x = 7.67893 ±

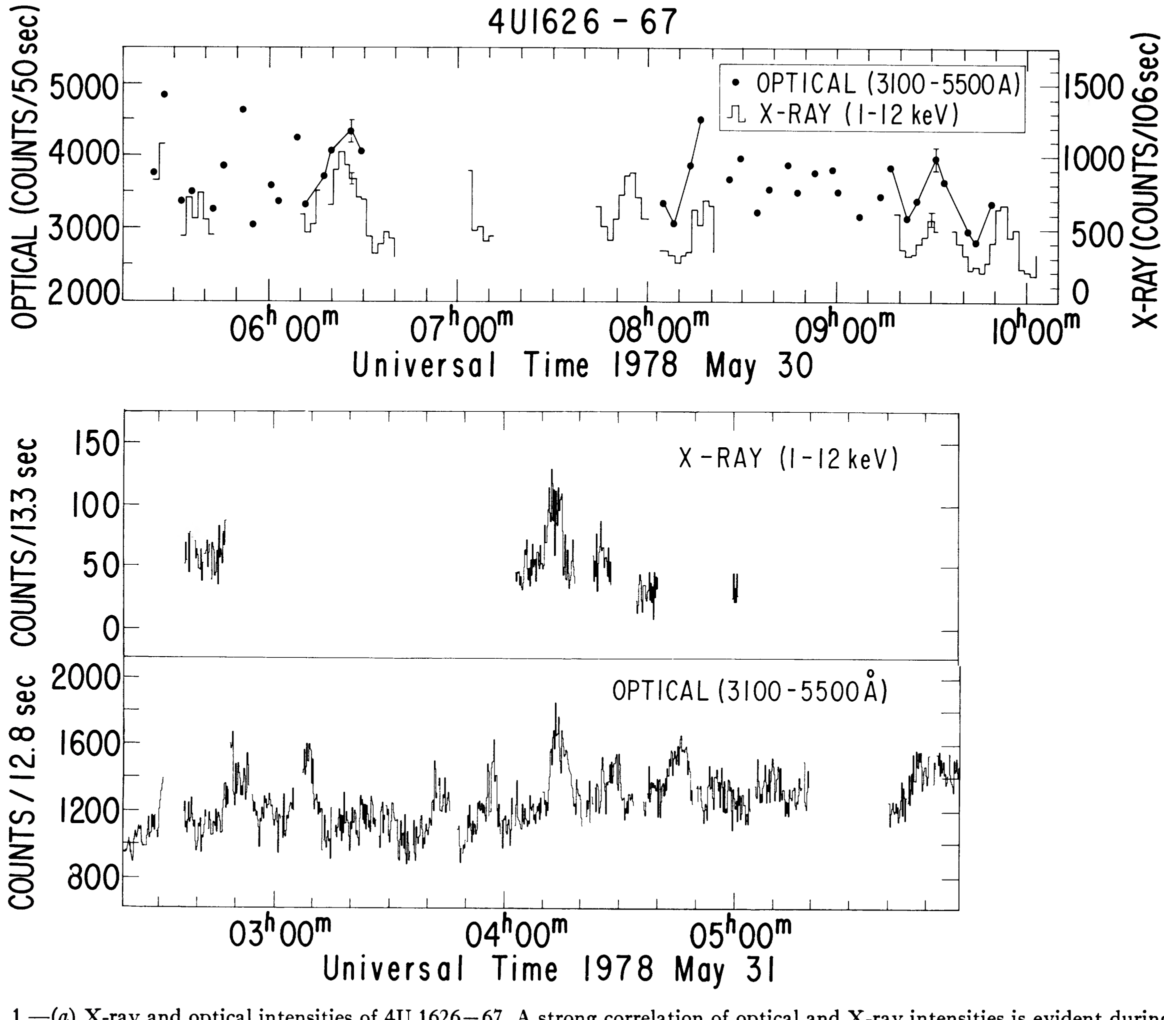

FIG. 1.—(*a*) X-ray and optical intensities of 4U 1626−67. A strong correlation of optical and X-ray intensities is evident during three intervals of extended simultaneous coverage (indicated by solid lines connecting the optical data points). An approximate X-ray background count rate of 1025 counts per 106 s has been subtracted as well as a precisely determined optical background rate which increased steadily from 11,000 to 26,000 counts per 50 s during the course of the observations as a result of moonlight. (*b*) X-ray and optical data for 1978 May 31 presented at a time resolution of 13 s. An intense X-ray/optical flare occurred at ~04^h10^m. The optical data clearly show the ~20 minute quasi-periodic flaring behavior characteristic of the source (see text). Average background count rates have been subtracted (B_x = 125 counts per 13.3 s; B_{opt} = 2350 counts per 12.8 s). However, the optical data have not been corrected for the effect of increasing moonlight, which caused the net counting rate to rise steadily by ~35% between 2^h and 6^h UT.

0.00002 (1 σ) s on 1978 May 29.9 UT. Earlier determinations of the period are given in Joss, Avni, and Rappaport (1978) and Pravdo *et al.* (1979).

Fourier analysis of the four hours of optical data shown in Figure 1*b* revealed a peak with a statistical significance of 5.5 σ at the X-ray period. The optical data were folded at 20 trial periods near the X-ray period, and the statistical significance of the resultant pulse profiles was computed using a simple χ^2 test (Ilovaisky, Motch and Chevalier 1978). The heliocentric optical period found in this way is $P_{\rm opt} = 7.6795 \pm 0.0010$ (1 σ) s on 1978 May 31.2 UT. The optical and X-ray periods agree to well within the 1.0 ms uncertainty in the optical period. This corresponds to a limit on the line-of-sight velocity difference between X-ray and optical emitting regions of ~39 km s^{-1} (1 σ).

The optical data were then folded at the better-determined X-ray pulse period to form the average pulse profile shown at the top of Figure 4. The resulting pulse profile is featureless and has a full amplitude of 3.0% of the average flux and a pulsed fraction of 1.5%. It is very similar to the one derived by Ilovaisky, Motch, and Chevalier (1978) using data taken 28 days earlier, and is consistent with the 3% upper limit (3 σ) obtained by Grindlay (1978) a year earlier. For comparison, we note that the pulsed fraction of the 1.2–3 keV X-ray pulse profile has a full amplitude of 33% and a pulsed fraction of 22%. A visual inspection of Figure 4 shows that the optical pulse is in phase with low-energy (1.2–3 keV) pulse and high-energy pulses (8–19 keV and 19–30 keV) and is ~180° out of phase with the mid-energy pulses (3–6 keV and 6–12 keV). A cross-correlation analysis gives the following formal lag (+) or lead (−) times of the optical pulse relative to each of the X-ray pulses expressed as a fraction of a 7.7 s period: 1.2–3 keV, +0.03; 3–6 keV, +0.53; 6–12 keV, +0.63; 8–19 keV, −0.04; 19–30 keV, −0.03; (the ~1 σ uncertainty due to counting statistics and the coarseness of the bins used in the analysis is ±0.02 in each case). The phase difference between the optical and the 1.2–3 keV X-ray pulsations, which will be used in § IV, is <0.07 (2 σ) or <0.5 s (2 σ).

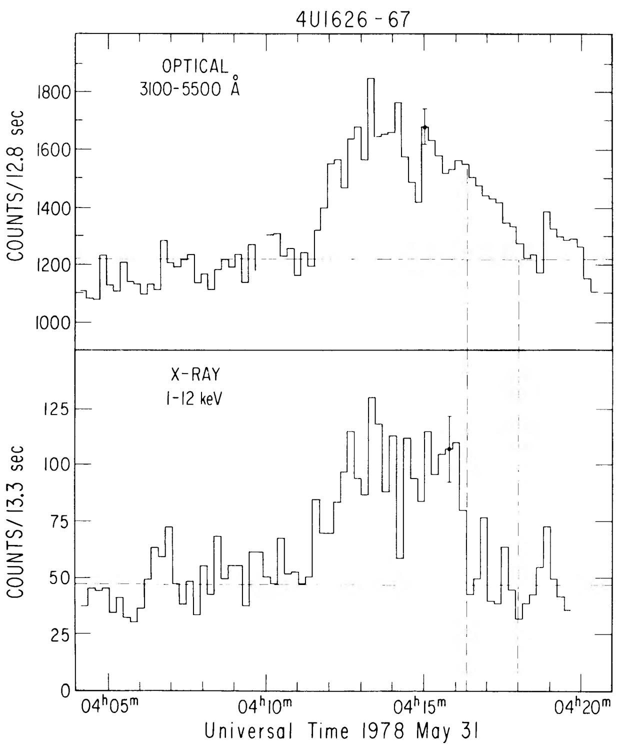

FIG. 2.—Blowup of the prominent X-ray/optical flare shown in Fig. 1*b*. Approximate X-ray and optical background count rates have been subtracted. During the flare the X-ray intensity increased by a factor of ~3, whereas the optical intensity increased by only ~50%. Although the onset times are about the same at X-ray and optical energies, the duration of the optical flare is ~1.5 minute greater. The approximate X-ray and optical intensities of the source just prior to the flare are indicated by horizontal dashed lines.

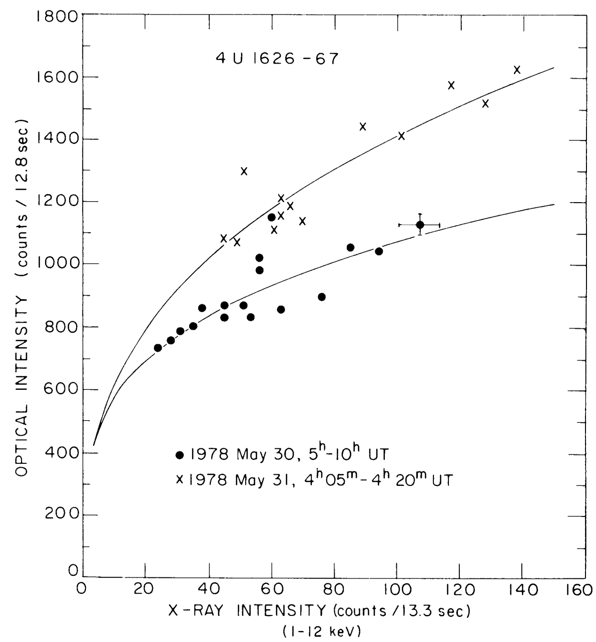

FIG. 3.—Optical intensity (3100–5500 Å) *versus* X-ray intensity (1–12 keV) for all the simultaneous observations shown in Fig. 1*a* (*dots*) and Fig. 2 (*crosses*). Although the intensities are expressed in counts per 13 s, each data point corresponds to a ~50 s average. The smooth curves are power-law fits to the data (see text).

IV. DISCUSSION

In the discussion below we show first that most of the observed optical emission is due to the conversion of X-rays into light, second that a substantial fraction of the optical emission comes from within ~0.5 lt-sec of the neutron star, and third that this emission cannot come from the X-ray heated surface of a companion star and is thus most likely due to an accretion disk. We note that the optical emission cannot originate in the small (~10^6 cm) X-ray emitting region (cf. Grindlay *et al.* 1978).

a) Conversion of X-rays into Light

For several reasons it seems likely that most and possibly all of the observed optical emission is due to the conversion of X-rays into light. Energetically this is reasonable since $L_x/L_{\rm opt} \approx 2000$. Also, the optical and X-ray intensities are strongly correlated on time scales from seconds to tens of minutes (Figs. 1–4), and at flare maximum at least a third of the total light from the system is directly attributable to the X-ray flare emission. Furthermore, for distances $\sim$10 kpc the faintness of the counterpart ($V \approx 18.5$), the extremely blue colors, and the low extinction rule out main-sequence or supergiant companions as the dominant source of the optical emission (McClintock *et al.* 1977; Joss, Avni, and Rappaport 1978).

b) Location of the Optical Emitting Region

There is a striking phase correspondence between the phases of the optical pulsations and the X-ray pulsations as measured at various energies (Fig. 4). The optical pulse agrees in phase and is similar in appearance to the high-energy (8–30 keV) pulse. However, it is very unlikely that the optical pulsations are driven by the 8–30 keV flux, since the time required to reprocess hard X-rays into light is $\sim$10–100 s, which is greater than the pulse period (Chester 1979). We also consider it unlikely that the optical pulsations are driven by the mid-energy (3–12 keV) X-ray pulsations because of the $\sim$180° phase difference and the very dissimilar pulse shapes. We therefore conclude that the optical pulsations are probably driven primarily by the 1–3 keV X-ray pulsations which are reprocessed promptly ($\lesssim$1 s; Chester 1979) and which differ in phase by $\lesssim$0.5 s (2 σ).

Applying the relationship derived in § III*a* for the soft X-ray flares ($I_{\rm opt} \sim I_x^{0.21}$) to the 33% full amplitude of the 1–3 keV pulsations gives a predicted full amplitude for the optical pulsations of 6.2%. This is twice the observed value of 3.0%. The lower optical modulation of the pulsations relative to the flares may be due, for example, to a partial cancellation caused by the antiphased 3–12 keV flux (Fig. 4), or to the effects of light travel time in the optical emission region. In any case, the flare data indicate that at least half and possibly all of the pulsed 1–3 keV flux is converted to light within a small ($\lesssim$0.5 s) light travel time of the compact source. Furthermore, the unpulsed 1–3 keV flux will be reprocessed to light in the same physical regions and with the same efficiency as the pulsed flux, assuming that both are created near the surface of the compact object. The total (unpulsed plus pulsed) 1–3 keV flux comprises $\sim$50% of the total photon flux and $\sim$15% of the total energy flux (sub-keV X-rays also may be important; see Pravdo *et al.* 1979 for observations). In addition, a significant portion of the flux above 3 keV will be converted to light in the same regions as the 1–3 keV radiation. From the evidence above we conclude that a *substantial fraction (a minimum of $\sim$8%[3]) and possibly all of the optical emission is produced within $\sim$0.5 lt-sec or 1.5×10^{10} cm of the neutron star.* We note that at this distance from a $\sim$1 $M_\odot$ neutron star the orbital period and velocity are about 15 minutes and 1000 km s^{-1}, respectively. Therefore, since the optical pulse profile shown in Figure 4 is an average over $\sim$4 hours of data, it is also an average over many ($\gtrsim$ 15) orbital periods of an accretion disk, dwarf star, or other hypothetical optical emitting region.

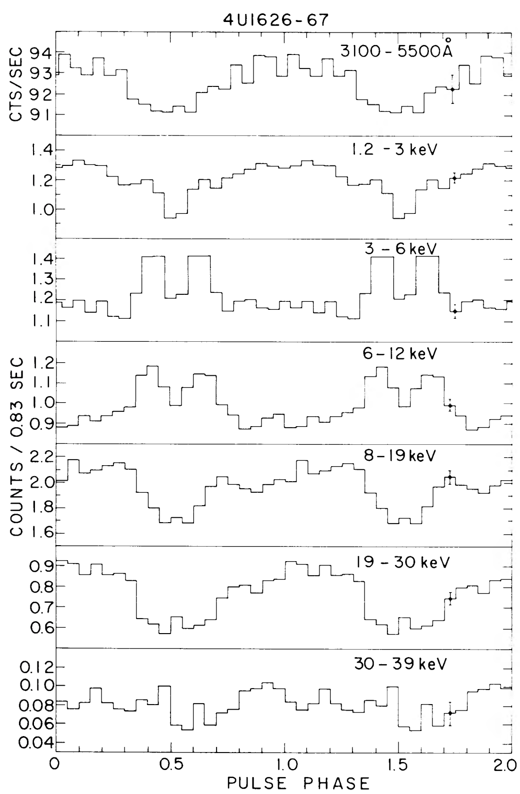

FIG. 4.—The top curve is an average broad-band optical pulse profile which was derived from the data shown in Fig. 1*b*. The six average X-ray pulse profiles below were derived from data obtained during 1978 May 29.4–30.8 UT. The data are folded into 20 bins modulo the 7.68 s pulse period and shown repeated in a second set of bins. Approximate background counting rates have been subtracted. Note the excellent phase agreement between the optical pulse and the low-energy (1.2–3 keV) and high-energy (8–30 keV) X-ray pulses.

c) Nature of the Emitting Region

There are several facts which rule out the possibility that the optical emission from within $\sim 1.5 \times 10^{10}$ cm is due to the heated surface of a companion star. First, for an assumed orbital separation of 1.5×10^{10} cm, all nondegenerate, nuclear burning stars would grossly overfill their Roche lobes (Paczýnski 1971; Allen

[3] The 8% minimum corresponds to reprocessing half of the 1–3 keV energy flux, which is 15% of the total energy flux, into light. We have assumed that for the same energy flux soft X-rays and hard X-rays are equally effective in producing optical radiation.

1973). Second, the large orbital velocity of a companion star, $\gtrsim 1000$ km s^{-1}, greatly exceeds the 39 km s^{-1} limit on the relative velocity of the X-ray and optical emission regions (see § III*b*) unless the orbital inclination is $\sim 2°$ (chance probability $< 10^{-3}$). Third, an effect that is due to the beating of the pulse and orbital periods and is independent of the Doppler effect would be expected to shift the optical pulse period away from the X-ray pulse period by a constant offset, $|\Delta P| = P_{\rm pulse}/P_{\rm orbital}$. For an orbital period of $\lesssim 15^{\rm m}$, corresponding to an orbital radius of $\sim 1.5 \times 10^{10}$ cm for a 1 $M_\odot$ neutron star, the predicted shift in the optical pulse period is $|\Delta P| \sim 60$ ms which exceeds the observational limit given in § III*b* by a factor of 60. The effect is independent of the orbital inclination of the system and rules out all nongenerate and degenerate stars as well as discrete bright blobs of orbiting gas. We therefore conclude that the optical emission from within $\sim 1.5 \times 10^{10}$ cm is not due to a star of any kind. It is probably due instead to an accretion disk for which the arguments given above do not apply.

d) Conclusion

The X-ray Doppler studies mentioned in § I indicate that 4U 1626−67 is a very small system, perhaps an order of magnitude smaller than a typical U Gem system; however, these studies provide no evidence for the existence of an optical companion. Likewise, a companion has not been detected in photometric and spectroscopic searches for its intrinsic stellar emission (§ IV*a*; work in progress), nor has one been detected in the study of the reprocessed radiation presented in this paper. Apparently, the optical emission in 4U 1626−67 (and probably in the bursters and related sources as well) is strongly dominated by the disk, and unfortunately the low-mass companion, which acts only as a mass donor, remains elusive.

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Claude R. Canizares, Fuk K. Li, and Jeffrey E. McClintock: Department of Physics and Center for Space Research, Room 37-521, Massachusetts Institute of Technology, Cambridge, MA 02139

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