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OPTICAL IDENTIFICATION OF 4U 1608−52

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ABSTRACT

The probable optical counterpart of the recurrent flaring (or transient) X-ray source 4U 1608−52 was discovered as a $m_I \approx 18.2$ object on a deep IV-N plate obtained with the CTIO 4 m telescope on 1977 August 24 UT. Comparison with a nearly identical 60 minute exposure IV-N plate obtained on 1976 August 28 UT reveals that this object was then fainter than the plate limit and so must have brightened by more than 1.8 mag between 1976 August and 1977 August. The object is within the $\sim 10'' \times 20''$ combined error box obtained by *SAS 3* and *HEAO 1* for 4U 1608−52, which underwent a transient source outburst in 1977 July. Constraints on source models are discussed, and if a galactic source ($r \lesssim 20$ kpc), the object is not a typical galactic nova. A model invoking preoutburst ejection of an absorbing shell may be implied for this and other recurrent X-ray "novae" (e.g., Aql X-1 and 4U 1630−47). Reduction of the error boxes for the X-ray bursters XB 1608−52 and Aql MXB, or detection of bursts from 4U 1630−47, is needed to demonstrate any relationship between recurrent transients and bursters.

Subject headings: stars: novae — X-rays: bursts — X-rays: sources

The normally weak X-ray source 4U 1608−52 = MX 1608−52 (Forman *et al.* 1978; Markert *et al.* 1977) either displays an extraordinary range of characteristics and time scales of variability or there are at least two X-ray sources near $l^{II} = 330^\circ.9$, $b^{II} = -0^\circ.8$. Attention was first called to this region of the galactic plane as the location of a weak X-ray source by Matilsky, Gursky, and Tananbaum (1973). Ricker *et al.* (1976) have reported a 1972 detection of a hard X-ray (more than 30 keV) source in this region in which a source was later detected and located at ~2–10 keV by *Uhuru* (Forman *et al.* 1978) and *OSO 7* (Markert *et al.* 1977). Increased interest in this source (or sources) was generated when Kaluzienski *et al.* (1975) reported the *Ariel 5* detection of a bright "new" transient X-ray source within ~3° of (l^{II}, b^{II}) = (331°, −1°), but perhaps most noteworthy was the discovery by Belian, Conner, and Evans (1976) of an X-ray burst source whose larger (~3° × 5°) error box included 4U 1608−52. The "Norma burster" was confirmed by Grindlay and Gursky (1976) to have the rapid rise times (less than 2 s) characteristic of other burst sources (though the burst decay times of ~100 s were longer than usual). These *Uhuru* observations significantly improved the burster location to be within a $0^\circ.6 \times 5^\circ$ region centered on the 0.015 square degree location obtained (Tananbaum *et al.* 1976) for the steady source 4U 1608−52. Tananbaum *et al.* also reported the *Uhuru* detection of flares (possibly bursts) from within a much smaller region ($\sim 0^\circ.1$) of 4U 1608−52.

Accordingly, we began optical observations at CTIO in 1976 April in an attempt to identify the X-ray source(s) in this region. These observations (*I*-band photography, 1 m telescope, and image-tube camera) limited the brightness of any obscured globular cluster in the Norma region (see Grindlay and Gursky 1976). In an effort to extend these limits still further and search for possibly extended objects in or near the error box, we began a program of deep IV-N photography of the Norma region in 1976 August, with the CTIO 4 m telescope. On 1976 August 26 and 28, 60 minute exposures were obtained with IV-N plates hypersensitized with a 1.2% strong ammonia bath (cf. Liller 1978). An RG 695 filter was used so that the bandpass was ~7000–9000 Å, and limiting *I* magnitudes recorded were $m_I \sim 20.0$. No obvious globular clusters were found in the ~1° circular field (centered on 4U 1608−52), though an apparently diffuse object with $m_I \sim 19$ was found at $\alpha_{1950} \approx 16^h08^m.1$, $\delta_{1950} \approx -52^\circ05'.5$, which is within the larger error box for the burst source (Grindlay and Gursky 1976). We shall discuss this result, together with other similar diffuse objects found (on IV-N plates) in or near other burster error boxes elsewhere.

In 1977, July the *SAS 3* X-ray observatory found that a "new" transient source with a ~2–10 keV intensity of ~1.1 times that of the Crab Nebula had appeared in the Norma region (Clark and Li 1977). An accurate RMC position was soon obtained (Doxsey, Clark, and Li 1977) with *SAS 3*. The X-ray source location circle was centered at

$$\alpha_{1950} = 16^h08^m51^s.,\quad \delta_{1950} = -52^\circ18'01'' \qquad (1)$$

and, with a 30″ radius, this "transient source" position was entirely contained within the 0.015 degree² error box of 4U 1608−52 (Tananbaum *et al.* 1976; Forman *et al.* 1978). It was then almost certain that 4U 1608−52 had brightened from its "normal" intensity of at most

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$\sim$10 *Uhuru* counts s^{-1} to $\sim$1000 counts s^{-1} and that this was probably a recurrence of the similarly transient behavior observed in 1975 by Kaluzienski *et al.* Because of the nova-like increase in X-ray brightness, it was obvious that a renewed search for an optical counterpart should be made immediately. With the kind cooperation of F. Schweizer, a 45 minute exposure B plate was obtained on 1977 July 13 with the 0.6 m Curtis Schmidt telescope. We also asked M. Liller, then at CTIO, for a deep red or infrared plate, but cloudy weather intervened. Blinking the blue plate against the (comparably deep) *ESO B* plate revealed that no stars within or near the *SAS 3* position had changed in B magnitude down to $m_B \sim 21$. However, on 1977 August 24, one of us obtained a 60 minute exposure IV-N plate of the Norma field with the CTIO 4 m telescope. The plate was hypersensitized with a 1.7% $AgNO_3$ bath (see Liller 1978), and very comparable (to within $\sim$0.2 mag) limiting sensitivity as compared with the 1976 August IV-N plates was obtained. Blink comparison of the 1976 and 1977 IV-N plates then revealed, as already reported (Grindlay 1977*a*), a "new" stellar image $\sim$2 mag above the plate limit on the 1977 plate and thus a prime candidate for the optical counterpart of 4U 1608$-$52.

The candidate optical counterpart is located at

$$\alpha_{1950} = 16^{\mathrm{h}}08^{\mathrm{m}}52^{\mathrm{s}}.2, \quad \delta_{1950} = -52°17'43'', \qquad (2)$$

with an uncertainty of $\sim\pm0''.5$, and is thus well within the original *SAS 3* position of Doxsey *et al.* This is evident in Figure 1 (Plate L3), where we show 20 times enlargements ($0''.93$ mm^{-1}) of the 1976 and 1977 IV-N plates and have marked the optical object and X-ray error circle. The *SAS 3* position has been further refined (Apparao *et al.* 1977) to have the same center (eq. [1]) but a 20$''$ radius, so that the optical position (eq. [2]) is just on the edge of the final *SAS 3* position circle. Subsequent to our observations, the scanning modulation collimator experiment on *HEAO 1* has further refined the X-ray position such that the *SAS 3* and *HEAO 1* positions combined yield a $\sim10'' \times 20''$ region containing our candidate (Fabbiano *et al.* 1978). Thus the X-ray and optical positions are completely self-consistent.

We have measured the 1977 plate with an iris photometer and derived an apparent I magnitude $m_I \sim 18.2 \pm 0.2$ for the optical object (*note:* the magnitude estimates given by Grindlay [1977*a*] were erroneously listed as "red-infra-red" but should have been approximate equivalent visual magnitudes), which is more than 1.8 mag above the plate limit. Since the limiting magnitudes of the two 4 m plates are very nearly the same (see Fig. 1), and since the optical object is not visible on the 1976 plates, we infer that the apparent I magnitude increase was *at least* 1.8 mag. We have calibrated the I magnitudes and iris photometry reduction by our direct photoelectric photometry of several stars within the error box as well as a cross calibration with the *ESO B* plate, using a magnitude sequence (Thackeray, Wesselink, and Harding 1962) for the nearby cluster NGC 6067. Although the poorer seeing or focus (hence larger images) on the 1976 plate distorts the relative brightness estimates of unresolved double stars owing to the Eberhard adjacency effect, the candidate object is well separated from the surrounding (triangle of) stars, and no image distortions are expected. The blink comparison revealed that no other resolved stars in or near the X-ray position changed in relative brightness by more than $\sim$0.2 mag. This, combined with the observed surface densities (versus magnitude and position) of long-period variable stars in this region of the plane (Plaut 1965), makes it very improbable that our optical candidate is a field variable star and not associated with the X-ray source. This is further supported by the fact that the optical candidate is also not visible on our comparably deep 1 m telescope I-band image-tube plates obtained on 1976 April 8 and June 6 when the X-ray source was also not active.

We can set a lower limit on the reddening and extinction of the object by noting that it was definitely not visible on the CTIO Schmidt plate (requiring $m_B \geq 21$) and apparently not visible on the UK Schmidt plate ($m_B \geq 22$) as reported by Hawarden (1977). Thus $(B-I) \geq 3.85$. If the object were similar to an optical nova, as possibly suggested by the X-ray relative increase and rate of decline (cf. X-ray fluxes given by Kaluzienski and Holt 1977), then the optical emission would have reached $M_v \sim -6$. Assuming its unreddened color is $(B-V)_o \approx 0.3$ or like that of the X-ray nova A0620$-$00 50 days after maximum (Whelan *et al.* 1977), then a normal reddening law (Johnson 1968) would imply $A_v \geq 4.47$. The observed apparent magnitude of 4U 1608$-$52, assumed intrinsic color, and this lower limit of extinction would then only limit the distance to be $r \lesssim 237$ kpc.

A very approximate upper limit estimate for the extinction and thus minimum distance can be obtained by using the measured low-energy X-ray cutoff energy (Tananbaum *et al.* 1976) of 4U 1608$-$52 and the implied (Gorenstein 1975) *maximum* value of $A_v \leq 7.9$ mag. Note that this is a maximum interstellar absorption for the quiescent source and that any local absorption in the quiescent source reduces this value. The above assumptions for M_v and color would then give a distance of at least $\sim$89 kpc, and for such an extragalactic transient source the X-ray flux (Kaluzienski and Holt 1977) requires $L_x \sim 10^{40}$ ergs s^{-1}. However, since $b^{\mathrm{II}} \sim -1°$, the source is very likely galactic ($r \lesssim 20$ kpc) with $L_x \sim 10^{38}$ ergs s^{-1}, and so if a nova ($M_v \sim -6$), it must have produced an absorbing shell with $A_{v,\mathrm{shell}} \approx 3.2$ mag, which should have *increased* the column density measured (after the outburst) by the low-energy X-ray cutoff to be $N_{\mathrm{H}} \sim 2.5 \times 10^{22}$ cm^{-2}. Thus X-ray spectra recorded near the outburst are of crucial interest. Without this added intrinsic absorption, the source could be galactic only if $M_I \geq -3.3$ and, assuming $(V-I)_o \approx +0.5$, then $M_v \geq -2.8$. In this case, the 4U 1608$-$52 optical candidate is *not* a typical nova, and so the optical emission is either intrinsically faint or self-absorbed.

The observed optical flux and estimated optical absorption $4.5 \lesssim A_v \lesssim 7.9$, when compared with the nearly simultaneous measure of the X-ray flux (Kaluzienski and Holt 1977) with intensity $\sim$0.5 Crab, give

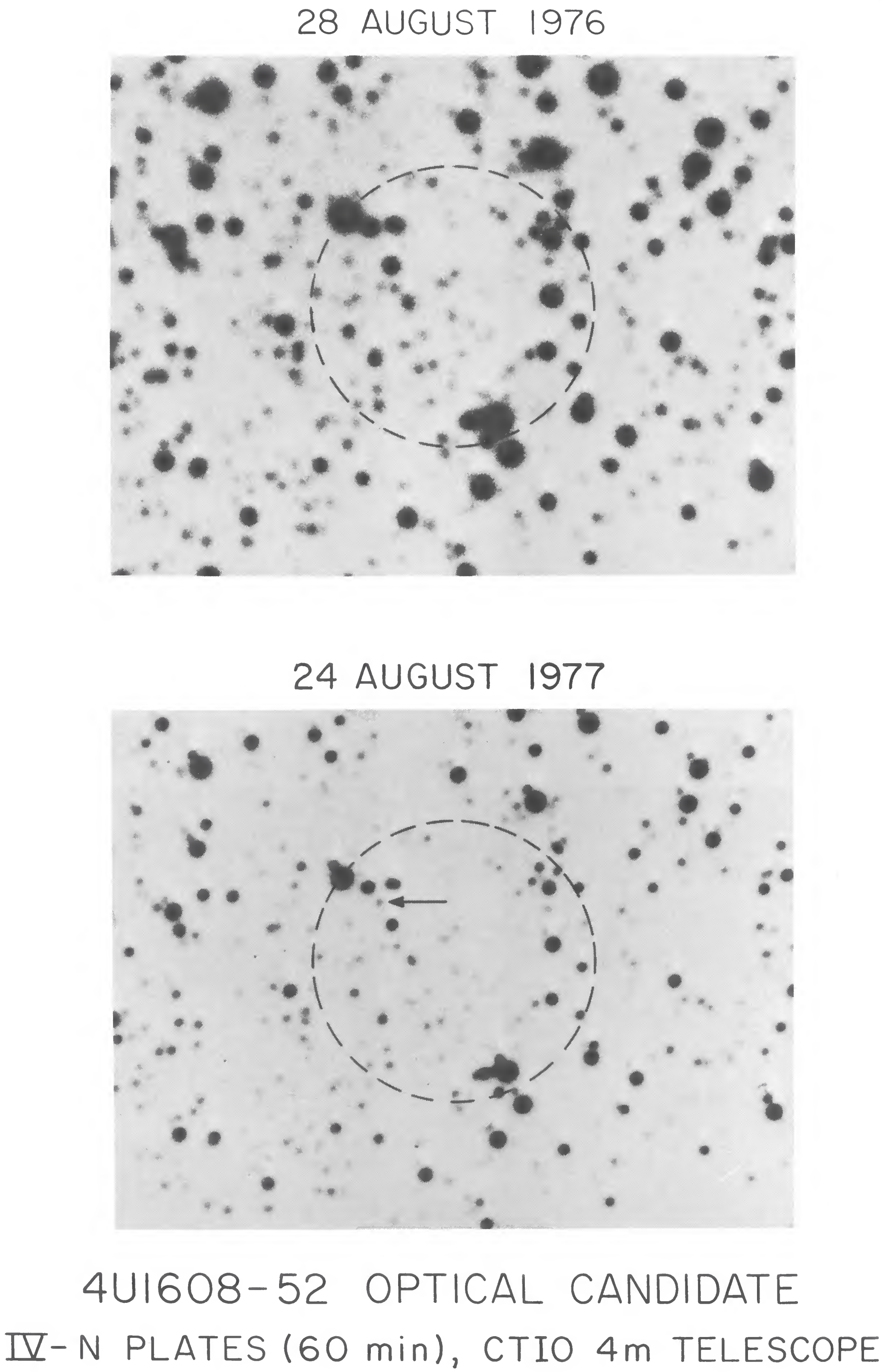

FIG. 1.—Enlargements (20 times or 0."93 mm^{-1}) of IV-N plates (~7000–9000 Å) of the 4U 1608−52 field obtained with the CTIO 4 m telescope on 1976 August 28 UT (*top*) and 1977 August 24 UT (*bottom*). North is up and east is to the left. The *SAS 3* error box (Doxsey *et al.* 1977) shown is 60" in diameter and has been further refined by Apparao *et al.* (1977) to a 40" diameter circle concentric with that shown. The *HEAO 1* position (Fabbiano *et al.* 1978) obtained after our observations further reduces the error box and also contains our candidate. The candidate optical counterpart for 4U 1608−52 is marked on the 1977 plate but is not visible on the pre–X-ray outburst 1976 plates with nearly identical limiting magnitude and so must have brightened by more than 1.8 mag to $m_I \approx 18.2$ mag.

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an X-ray/optical luminosity ratio in the range $10 \lesssim L_x/L_{\rm opt} \lesssim 200$. This is a factor of at least ~10 below the corresponding value (i.e., at ~50 days after maximum) for A0620−00 (Whelan *et al.* 1977), further suggesting that 4U 1608−52 is a different type of object or that it shows less intrinsic absorption. We also note that the possible recurrence time for transient outbursts from 4U 1608−52 is only ~1.7 years (1975 November through 1977 July), which is much shorter than the recurrence time for either usual recurrent novae (Allen 1973) or A0620−00 (Eachus, Wright, and Liller 1976), but is almost identical with that for the recurrent transient source 4U 1630−47 (Jones *et al.* 1976). Finally, the 4U 1608−52 source differs from A0620−00 in that X-ray flaring (on time scales ≤ 1 day) is observed (Kaluzienski and Holt 1977) during its decline, which also maintained a more nearly constant average intensity (~0.3 Crab) for several months after the outburst.

Thus we conclude that 4U 1608−52 is probably not a typical transient source of either Type 1 (soft) or Type 2 (hard) as classified by Kaluzienski (1977), but could be similar to the other recurrent transient X-ray sources, e.g., Aql X-1 and 4U 1630−47. The optical luminosity could be similar to galactic novae if an absorbing shell is blown off the source prior to the outburst. The $A_{v,\,\rm shell} \sim 3$ mag absorption implied might then be obtained by, for example, a $\sim 10^{-6}\,M_\odot$ shell blown out to $r \sim 10^{14}$ cm in several months as can be inferred from the optical emission-line spectrum with broadened P Cygni profiles found (Grindlay 1977*b*) for the candidate identification of 4U 1630−47 just prior to a predicted outburst. The postoutburst optical emission would partially arise in this shell and an interior shell, rather than an accretion disk. A direct test of this model is, of course, to measure the optical extinction and/or low-energy X-ray cutoff before and after an outburst. Aql X-1, with its relatively bright (~20–17 mag) optical counterpart (Thorstensen, Charles, and Bowyer 1977), is better suited for such observations.

The nature of the central object and trigger mechanism is, however, not clear, since Kaluzienski (1977) has shown that recurrent transients are probably *not* consistent with either the eccentric binary or Mira variable hypotheses for recurrent accretion surges. Since 4U 1608−52 and the possibly related other recurrent transients (e.g., Aql X-1) have detectable "steady" emission between outbursts, we surmise that a crucial difference in these objects is the long-term effect of X-ray heating which might lead to enhanced accumulation of gas (and an absorbing shell) near the accretion radius. Although it is likely that a binary is involved as in normal novae and the X-ray accretion is supplied by mass transfer, it should be noted that binary periods in X-ray novae have not been conclusively established, since the ~7.8 day period for A0620−00 (Matilsky *et al.* 1976) was not confirmed by nearly simultaneous *Ariel 5* data (Griffiths 1977).

Finally, we note (for 4U 1608−52) that models for X-ray bursters and (possibly) transient sources involving supercritical spherical accretion onto a collapsed object in an interstellar cloud have also been proposed (Grindlay 1978) in which optical emission and wind outflows (yielding shells) can arise from X-ray heating. The resulting compact H II regions would usually (at ~10 kpc) appear stellar in size, and the optical spectra of these objects would not reveal any "normal" stellar absorption spectrum. Unfortunately, we were not able to obtain spectra of the 4U 1608−52 optical counterpart. Continued optical/IR monitoring is also needed, although the object may have now faded below detectable levels. Reduction of the error box for the burster possibly associated with 4U 1608−52 is then especially important, as this source may exhibit both bursting and transient source behavior (see also discussion by Fabbiano *et al.* 1978). Some support for this identification of a recurrent transient with a burst source comes from our comparison with Aql X-1, noted above, since Aql X-1 is also (nearly) within a relatively large burster error box—that for Aql MXB (Lewin *et al.* 1977). However, significantly improved positions for the bursters XB 1608−52 and Aql MXB are needed to identify them with the recurrent transient sources, since the present error boxes and galactic distribution of bursters would indicate at least 10%–20% probabilities of chance coincidence. An association of recurrent transients with bursters would predict that bursts should eventually be detected from 4U 1630−47 as well.

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