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ON THE OPTICAL SEARCH FOR THE X-RAY SOURCES CYG X-1 AND CYG X-2

In an attempt at identification, an optical search of the sky has been made near the new X-ray positions of Cyg X-1 and Cyg X-2 given in the previous Letter (Giacconi, Gorenstein, Gursky, and Waters 1967). Anticipating the results of the rocket flight, we obtained photographic plates in August, 1966, using the 48-inch Palomar Schmidt with the Haro-Luyten (1962) three-color-image technique. The plates covered an area 7° on a side and were centered near the early positions given by Bowyer, Byram, Chubb, and Friedman (1965).

The plates were inspected for objects which were peculiar in their ultraviolet intensity, adopting again the working hypothesis that the power spectrum of the source, expressed as energy per unit frequency, would be flat between the X-ray and optical region of the spectrum. The physical basis for such an extrapolation is X-ray and optical energy production by either bremsstrahlung in an optically thin plasma or by the synchrotron process for electrons possessing a flat energy distribution. This hypothesis had previously proved to be successful in the case of Sco X-1 (Sandage, Osmer, Giacconi, Gorenstein, Gursky, Waters, Bradt, Garmire, Sreekantan, Oda, Osawa, and Jugaku 1966; Johnson and Stephenson 1966). For that source extrapolation of the spectrum from the observed X-ray region of the 10–1 keV into the optical region ($\lambda = 5500$ Å) predicted $V = 11.8$, $B - V = +0.10$, $U - B = -0.91$ if no optical extinction were present, and indeed the optical image of Sco X-1 was seen at $\langle V \rangle \approx 12.7$, $B - V \approx +0.2$, and $U - B \approx -0.8$ values which are consistent with the prediction when the observed corrections for interstellar extinction and reddening of $A_v \approx 0.7$ mag, $E(B - V) \approx 0.23$, and $E(U - B) \approx 0.17$ are applied.

The parallel predictions for Cyg X-1 and Cyg X-2 are as follows: the X-ray intensity of both sources is about 20 times smaller than for Sco X-1 (although the sources may be variable) giving Δ mag $= 3.2$ compared to the Scorpio object. Therefore, in the absence of absorption, the optical counterpart of either object should appear at $V \approx 15.1$, $B - V \approx +0.1$, $U - B \approx -0.9$.

The optical absorption in front of the two sources is, however, not negligible. Cyg X-1 at $l^{\text{II}} = 71°$, $b^{\text{II}} = +3°$ is in a region of extremely heavy absorption with $A_v \geq 3$ mag. The optical image will, therefore, be faint and highly reddened with $V > 18$, $B - V > 1.0$, and $U - B > -0.2$. On the other hand, Cyg X-2 at $l^{\text{II}} = 87°$, $b^{\text{II}} = -11°$ is well out of the galactic plane, and there is no heavy, variable absorption visible on the *Palomar Sky Survey* prints. The cosecant law of galactic obscuration gives $A_v \approx 1.0$ mag, $E(B - V) \approx 0.25$, and $E(U - B) \approx 0.18$, if we adopt Hubble's half layer absorption of 0.25 mag. Consequently, the predicted magnitude and colors for Cyg X-2 are near $V = 16$, $B - V \approx +0.4$, $U - B \approx -0.7$.

While the predictions for magnitude and color hold quite independently from the angular size of the sources, the predicted surface brightness depends directly on it. The X-ray measurements themselves do not, in the case of Cyg X-1 and Cyg X-2, furnish an upper limit to the angular size and do not exclude the possibility that the sources may appear as nebulosities sufficiently extended to be undetectable. We have in this search assumed as an additional hypothesis that the sources would appear starlike. As noted in the previous Letter, this was not the case in the search for Sco X-1 where a minimum surface brightness could be computed on the basis of the X-ray data themselves.

Inspection of a 1° square field of the three-color plate in the Cyg X-1 region revealed no peculiar ultraviolet image to an estimated limit of $V \approx 18$ mag. Figure 1 (Plate L5) is a reproduction of the 48-inch Schmidt *Sky Survey* blueprint near the source. The size of the illustrated field is 4° by 5° and is centered about $\frac{1}{4}^\circ$ north and 1° east of the X-ray position, which is indicated by a square whose dimensions are ± 10 arc min on a side—the X-ray position being at the center. Our inability to detect the optical counterpart of Cyg X-1 may be due to the heavy obscuration in the field and cannot be considered as evidence against the working hypothesis. We are looking almost exactly along the inner edge of the local spiral arm (see, e.g., maps in Kerr and Westerhout [1964], Plate II and Fig. 9; and Sharpless [1964], Fig. 10)—a region known to be filled with heavy dust clouds in many normal Sb and Sc galaxies.

The search was apparently more successful in the case of Cyg X-2. A region 4° on a side, centered near the X-ray position, was inspected to $V \approx 18$ mag. Three candidate objects were found with peculiar ultraviolet properties, only one of which was near the new X-ray position, the other two being 0°.9 and 3°.2 distant. The first object is suggested as the tentative identification of Cyg X-2. It is marked in Figure 2 (Plate L6), which is an enlargement from the *Sky Survey* print. The illustrated area has dimensions of 19 by 25 arc min with the X-ray position at $\alpha(1950) = 21^h42^m48^s$, $\delta(1950) = +38°11'$ marked as a cross and with a portion of the error area shown as well. The optical candidate is at $\alpha(1950) = 21^h42^m36^s.91$, $\delta(1950) = +38°5'27''.9$ with an accuracy of about 0''.5 in both coordinates. The object is well within the X-ray error box. It is the prime candidate because of its peculiar colors of $B - V \approx +0.4$, $U - B \approx -0.4$ with $V \approx 15.5$ mag—values which agree well enough with those expected on the basis of our working hypothesis. The colors and magnitude have not been measured photoelectrically but have been estimated by eye from the three-image plate using two photoelectric stars on the same plate.

From the 48-inch Palomar Schmidt plates no evidence for variability could be derived. While we have as yet no physical basis for predicting variability, we felt that this was an important phenomenological characteristic of Sco X-1 that could perhaps be common to all objects belonging to the same class and, in particular, to Cyg X-2. At the suggestion of O. Manley, the variability of this object was investigated by Usher using plates from the Harvard plate collection. Only two collections of plates, those taken with the 8-inch Ross-Lundin lens (IR series) and those taken with the 3-inch Ross-Fecker lens (RH series) had more than one plate with the object above plate limit. The RH plates were more numerous but were of poorer photometric quality and no statements on small amplitude ($\lesssim 1$ mag) light fluctuations were possible. The IR series had better images, but only five plates were found which showed the candidate object. In addition to the candidate object, twenty stars shown in Figure 3 were measured on the Harvard Askania iris photometer. The probable error of a single measurement is ± 0.02 mag, but this indicates only the internal consistency of repeated measurements on a given plate and does not include systematic differences between plates. An approximate magnitude scale for the stars was established using the nearby Selected Area 41 and the *Palomar Sky Survey* prints. The total amplitude, Δm, of the deviations from the mean magnitude, $\langle m \rangle$, are given in Table 1 along with the standard deviations σ for twelve stars that bracket the candidate object in brightness. The comparison stars are listed in order of decreasing brightness. While σ increases toward plate limit, we see that objects 9 and the candidate object 10 show the greatest variation with amplitudes of 1.35 and 0.90 mag, respectively. On the assumption that the other eighteen stars do not vary, probable errors of ± 0.15 mag for $\langle m \rangle$ can be established. The finite time resolution of the plates could increase the amplitude, if the brightness fluctuations are of the order of the exposure time ($\sim$60 min).

The five IR plates cover a time interval of from November, 1939, to September, 1948. Two of the plates, IR 10778 and IR 10859, were taken 19 days apart. Figure 4 (Plate L7) presents a portion of these two plates from which the variability of objects 9 and 10

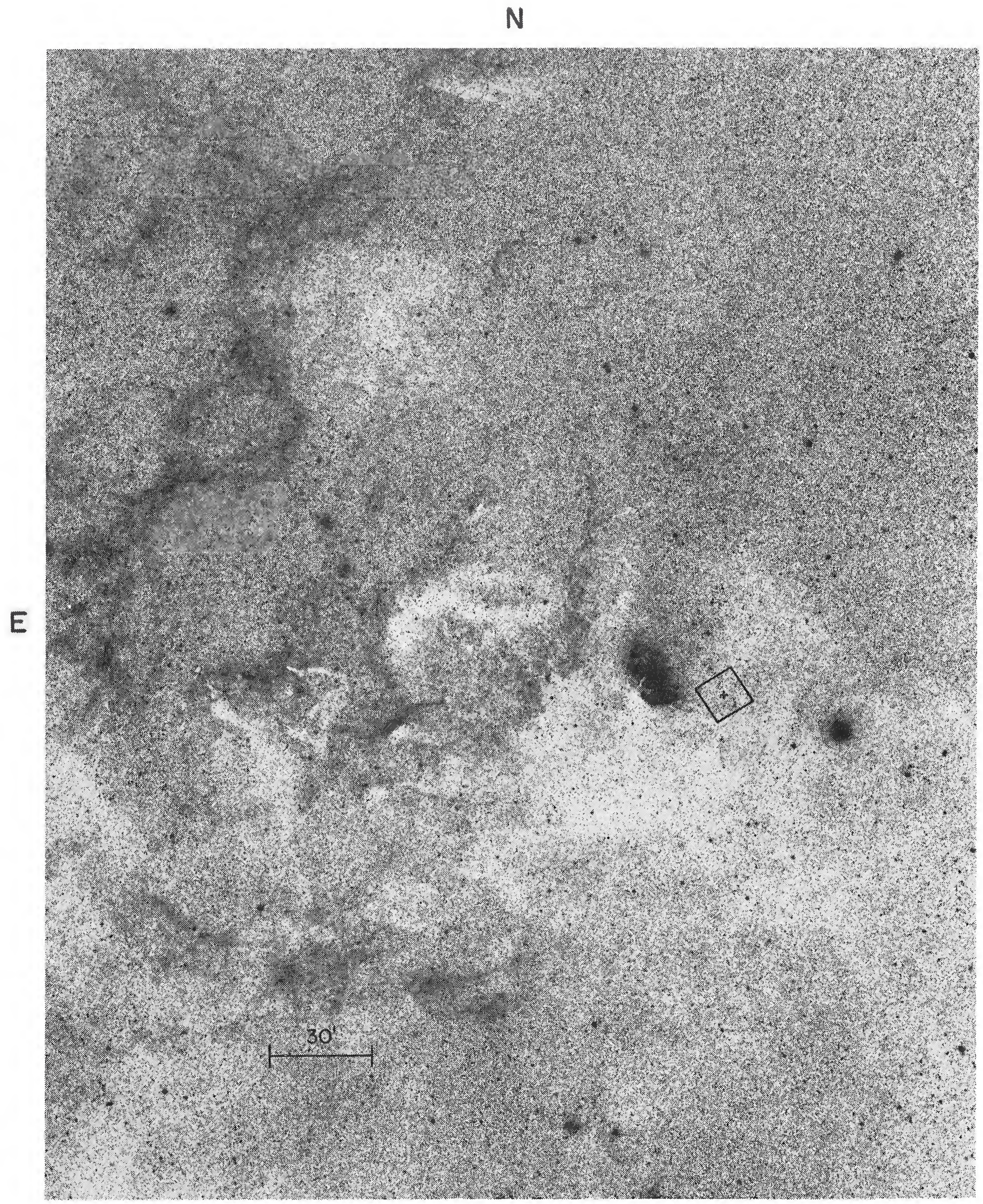

FIG. 1 —Reproduction of a 4° × 5° part of the Palomar Sky Survey blue photograph near the X-ray position of Cyg X-1. The marked square is centered on the X-ray position and is the actual area of uncertainty determined for the object. Copyright *National Geographic Society–Palomar Observatory Sky Survey.*

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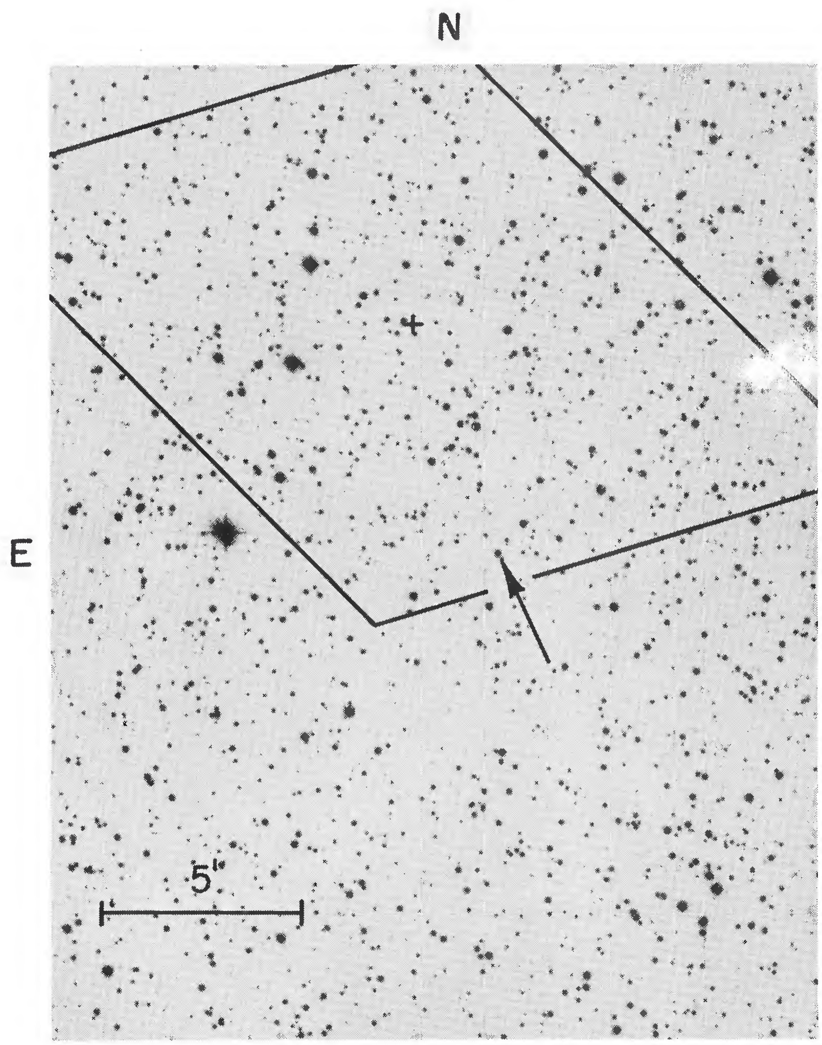

FIG. 2.—Enlargement of a 19′ × 25′ portion of the *Sky Survey* print near the position of Cyg X-2. The X-ray position is marked by a cross. The prime candidate optical object at $\alpha(1950) = 21^h42^m36^s.91$, $\delta(1950) = -38°5'27''.9$ is marked by an arrow. The X-ray error box is indicated. The elongation of the optical image of the candidate object is caused by a neighboring 19th-mag field star and is not due to an intrinsic structure of the candidate object itself.

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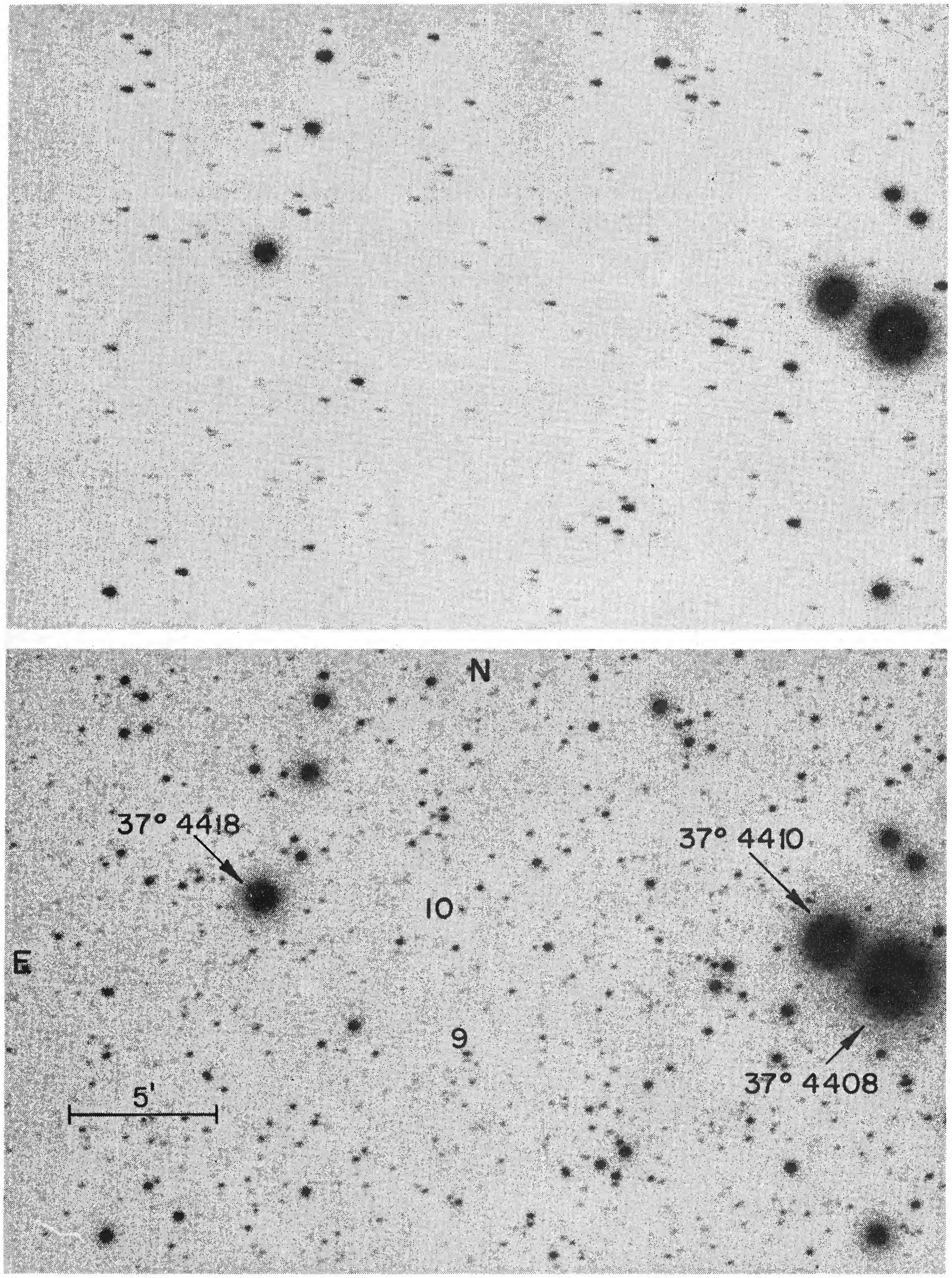

FIG. 4.—Portions of plates IR 10778 and IR 10859 taken on September 6–7 and September 24–25, 1948. The brightness fluctuations of objects 9 and 10 are clearly visible. The emulsion type is 103aO. The exposure times are 60 min for IR 10778 and 78 min for IR 10859.

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can be seen. The emulsion type is 103aO and the exposure times of the plates are 60 and 78 min, respectively.

Our conclusion is that the candidate object 10 varies. Although object 9 also varies, it is not considered as a candidate because its color index is quite red, as determined by inspection of a pair of blue and yellow plates taken simultaneously with the Damon patrol camera at Harvard and it has no peculiar ultraviolet excess on the 48-inch Schmidt plates.

The a priori probability of finding an optical object within the error box for Cyg X-2 that meets the predicted magnitude and color requirements, and that appears to be variable as well, is quite small. We believe that this represents strong evidence that the candidate object may, in fact, be the X-ray source. We recognize that the area of uncertainty around Cyg X-2 contains many objects brighter than +16 mag, albeit not with the correct color. This was not the case in the Sco X-1 identification, where the optical candidate was the brightest object in the error box.

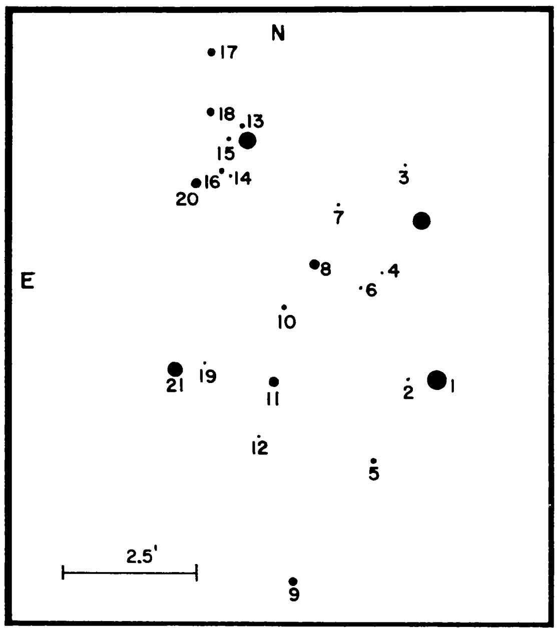

Fig. 3.—Finding chart for objects whose optical brightness fluctuations have been examined. Object 10 is the candidate.

TABLE 1

Standard Deviation σ and Total Range of Variability Δm from 5 Plates of the IR Series for 12 Stars, in Order of Increasing Mean Magnitude

Star	σ	Δm	Star	σ	Δm
21.........	0.11	0.25	18.........	0.09	0.20
20.........	.07	0.15	13.........	.11	.25
8.........	.07	0.15	10.........	.40	.90
17.........	.13	0.30	5.........	.13	.30
9.........	.60	1.35	16.........	.18	.40
11.........	0.07	0.15	15.........	0.27	0.60

In order to make a better comparison to Sco X-1 and to gain more confidence in this identification, all efforts will be made by the Mount Wilson and Palomar group to obtain spectra and photoelectric photometry of the candidate this season when the 21^{h} region passes out of conjunction with the Sun. The area around Cyg X-1 will also be more carefully inspected for evidence of the X-ray source.

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