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AN X-RAY SURVEY OF THE CYGNUS REGION

In order to localize and identify X-ray sources, we have scanned the Cygnus region with large-area proportional counters flown on an attitude-controlled sounding rocket. We find four X-ray sources in the region between $70° \leq l^{II} \leq 100°$, $-16° \leq b^{II} \leq +10°$ for which we have derived locations precise to about 10 arc min. Two of these sources, the most intense, were previously known; we report the two others as new sources, although they may have been observed previously in coarser surveys. The scanned region included Cyg A, the strong, extragalactic radio source, which is not observed to be an X-ray source. An optical search of two of the regions (described in the accompanying letter, Giacconi, Gorenstein, Gursky, Usher, Waters, Sandage, Osmer, and Peach 1967) has revealed an object at the location of the source Cyg X-2 which has visible light characteristics similar to those of the optical counterpart of Sco X-1 (Sandage, Osmer, Giacconi, Gursky, Waters, Bradt, Garmire, Sreekantan, Oda, Osawa, and Jugaku 1966; Johnson and Stephenson 1966). Another of the X-ray sources is in the Cygnus X radio region and along the Cygnus spiral arm. During the early portion of the same rocket flight, the region $-20° \leq l^{II} \leq 70°$, centered at $b^{II} = 0°$ was scanned and included the observation of Sco X-1. The data gathered in that region will be discussed in a forthcoming paper.

The existence of X-ray sources in Cygnus is already well established. The very first observations of celestial X-ray sources by Giacconi, Gursky, Paolini, and Rossi (1962) in June, 1962, in conjunction with observations by the same group in October, 1962, indicated the existence of a source in Cygnus (Gursky, Giacconi, Paolini, and Rossi 1963). Subsequently, Bowyer, Byram, Chubb, and Friedman (1965) of the Naval Research Laboratory (NRL) reported observing two X-ray sources in Cygnus during a June, 1964, rocket flight; Fisher, Johnson, Jordan, Meyerott, and Acton (1966) of Lockheed reported seeing a single source during an October, 1964, flight, and Byram, Chubb, and Friedman (1966) reported four sources based on an April, 1966, rocket flight, one of which was identified as Cygnus A. By comparing the data obtained during the June 1964 and April 1965 flights, Byram *et al.* (1966) reported that the source denoted as Cyg XR-1 had undergone a fourfold change in intensity. The locations of the sources as reported by the two groups are summarized in Figure 1. Other groups have also explored the Cygnus region with balloon and rocket-borne instrumentation to measure the spectra of the X-ray radiation originating in these regions, but with angular resolution too coarse to distinguish and locate discrete X-ray sources. Except for the identification of Cyg A, which now appears to be incorrect, none of the X-ray sources has been associated with visible or radio objects.

There were several reasons that made the Cygnus region an interesting one for observation. First, we wished to test our working hypothesis that many of the known galactic X-ray sources are similar in their optical characteristics to Sco X-1. The X-ray sources in Cygnus appear to be isolated and, thus, easier to localize than those near the galactic center where the X-ray source density is much higher. Second, the region contains many interesting visible and radio objects that might be X-ray sources; e.g., old novae, to which a connection is suggested by a current interpretation of the optical data on Sco X-1. Finally, as noted, Cyg A had been reported to be an X-ray source at a power level that greatly exceeded the visible and radio emission from the galaxy. Such an observation clearly required verification.

The instrumented rocket utilized to achieve these objectives was an Aerobee 150, flown from the White Sands Missile Range on October 11, 1966. The X-ray detectors were argon-filled, beryllium window proportional counters with an effective area of about 800 cm^2. The low-energy cutoff (counter efficiency <25 per cent) was about 1.5 keV and was determined by the thickness of the beryllium window of 9.1 mg/cm^2. The high-energy cutoff was about 12 keV and was determined by the gas filling of argon which had an equivalent thickness of 9.0 mg/cm^2. The energy resolution of the counters was 21 per cent, full-width half-maximum (FWHM) for 5.9 keV X-rays. Counter signals originating from penetrating particles were eliminated by the use of a veto signal from

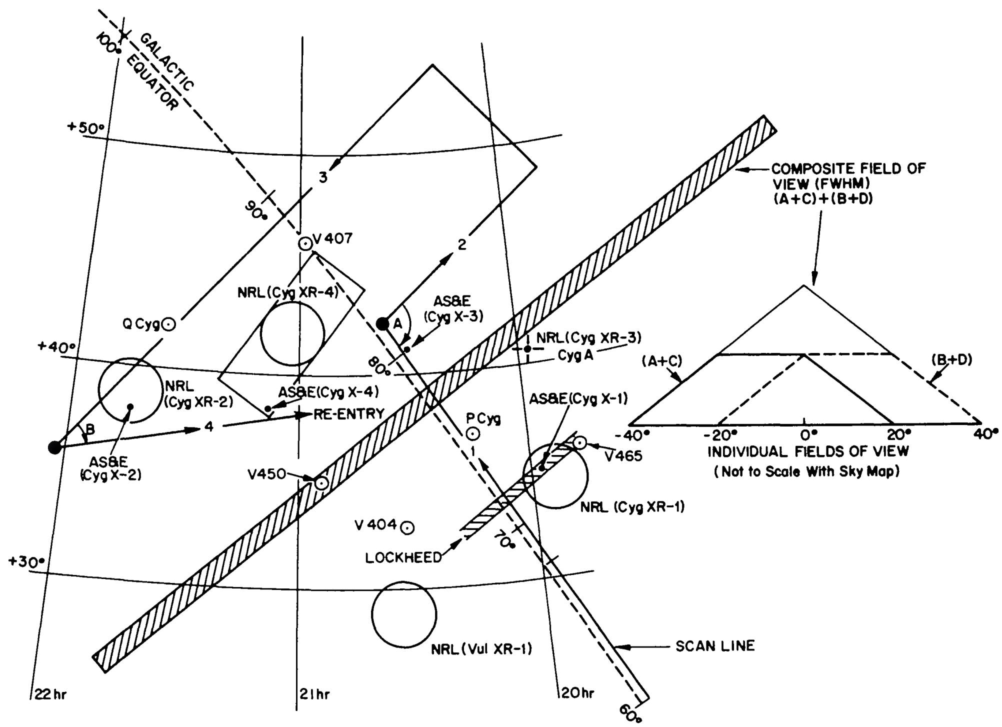

FIG. 1.—The lines of the center of the field of view of the X-ray detectors on the celestial sphere for the Cygnus portion of the flight are shown as a solid line with numbers and letters denoting the various maneuvers described in the text. The locations of the sources observed in this experiment (AS & E) are shown together with some previous determinations made by the NRL (Friedman, Byram, and Chubb 1967) and Lockheed (Fisher *et al.* 1966) groups. Several prominent novae found in the Cygnus region are shown as circles with a central dot. The insert labeled "Individual fields of view" gives the collimator transmission plotted as a function of angle from the center of the field of view in the direction of the long dimension.

a group of guard counters. All other signals were telemetered to the ground with their amplitudes preserved; however, only those signals corresponding to energies between 2 and 5 keV were used in the analysis leading to the location of the sources.

The detectors were arranged with two different fields of view corresponding to what will be referred to as the $(A + C)$ and the $(B + D)$ counters. The shapes and dimensions of the two fields were identical ($1° \times 40°$, FWHM) but did not exactly overlap. The centers were displaced by 20° from each other along the direction of the 40° dimension, as shown in Figure 1. Thus, a source traversal would appear simultaneously in the two sets of detectors, but the peak counting rate would be different depending on the location of the X-ray source within the field of view as the source was being traversed.

The observations were made by slowly traversing the Cygnus region along several different scan lines which were obtained by having the rocket maneuver between fixed points in the sky at preset rates. These lines (see Fig. 1) represent the position of the center of the field of view of the combined detectors. The long dimension of the fields of view was approximately perpendicular to the scan lines. Thus, along lines 1, 2, 3 and 4, a band of sky $\sim 40°$ width was scanned. The average rate of scan along these lines was 0.4°/sec, 0.23°/sec, 0.5°/sec, and 2°/sec respectively. To make the change in orientation required to go from line 1 to line 2 and from line 3 to line 4, the rocket was rotated about points A and B, respectively. During these rotations, a portion of a circular sector of $\sim 40°$ diameter was scanned. To make the change required to go from line 2 to line 3, the rocket was rotated in such a way to carry the X-ray axis in the direction of the long dimension of the X-ray field of view. The purpose of this maneuver was to reposition the detector axis in preparation for the scan along line 4.

The instantaneous attitude of the vehicle was obtained by photographing the star field at a 1-sec rate with a 16-mm camera that was equipped with a f/0.9, 25-mm focal length lens. The field of view of the camera overlapped that of the X-ray detectors. The magnitude of the faintest detectable stars was a function of the scan rate, and varied from about +3 mag to +6 mag. The orientation of the film plane was found by reference to a minimum of four stars in each frame. Whenever possible the validity of the orientation measurement was determined by comparing the calculated position on the film of those stars not used in the analysis with their measured position. The deviations between the two were typically 2 arc min and represent the reading error on the individual stars. The calculated orientation of the film plane, since it was based on measurements of a number of stars, should be better than this; in fact, the scatter in the curve that connects consecutive measurements of orientation (i.e., the scan line) was less than 1 arc min. The relative orientation of the X-ray detectors with respect to the film plane was determined by a pre-flight survey that utilized parallel beams of light and X-rays.

The X-ray data obtained during the times corresponding to the scans shown in Figure 1 are plotted in Figure 2. A number of peaks, each corresponding to the transit of an X-ray source, appears in the data. A peak was defined as a 1° region (i.e., one resolution element) in which the observed number of counts exceeded the expected background counts by at least three times the square root of the observed counts (3σ). The background level was obtained during the interval of 230–255 sec, a time when the detectors were viewing a region removed from the galactic equator and where no sources are apparent. The background, which mostly results from gamma-rays and the inefficiency of the anticoincidence counters, as well as a contribution from the isotropic X-ray background, was sensitive to the orientation of the vehicle and was observed to change slowly by about 20 per cent during the flight. These changes did not significantly affect our ability to select the peaks. As noted earlier, because of the offset of the detector axes, the peaks do not appear with the same intensity in the two sets of detectors. For example, the peak marked g appears much stronger in $(A + C)$ than in $(B + D)$, and the strong peak i in $(A + C)$ does not appear at all in $(B + D)$. The data are plotted as a function of time and the widths of the peaks vary according to the instantaneous rate of scan; e.g., peak a is much narrower than peak g. The actual angular widths are roughly as expected on the basis of the known angular response of the detectors to X-ray sources with angular sizes smaller than the angular resolution.

The data represent a series of one-dimensional scans across a region that is known to contain a number of discrete sources. Each peak in the data defines a line of position (actually the arc of a great circle) on which the source must lie. The relative counting rates in the two sets of detectors restrict the source position to a portion of the line of position; precise location is obtained from the intersection of two or more lines obtained during the several scans at different orientations. The locus of possible source positions for all the peaks in Figure 2 is drawn in Figure 3. The problem of pinpointing the sources is to find a unique set of locations that agree with the data. Not only must the sources be at the intersections of two or more lines of position, but the locations must also yield the correct relative source intensities as seen in the several traversals. We also keep

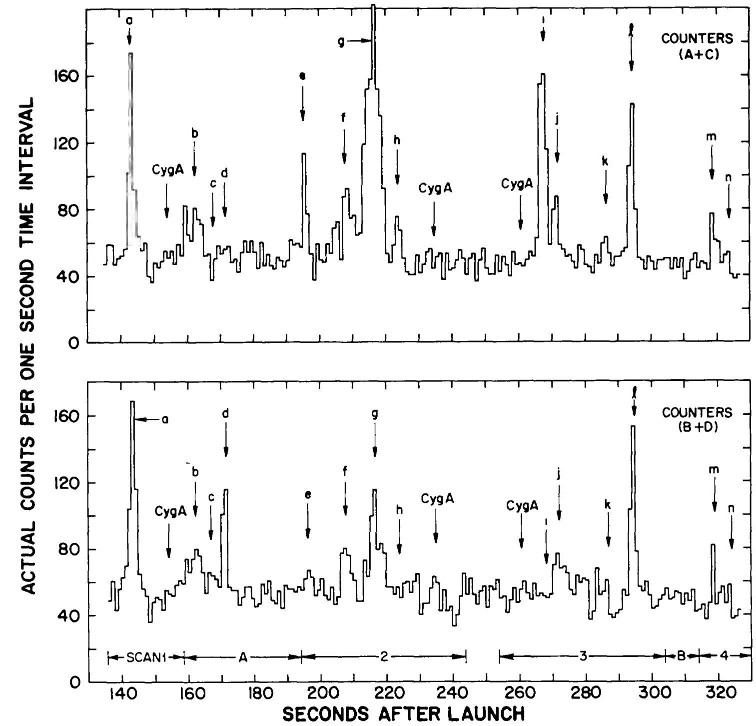

FIG. 2.—The histograms of actual counts per one second interval versus time for the Cygnus portion of the flight is shown for pulses falling within the photon energy interval 2–5 keV. The numbers and upper-case letters above the time scale refer to various maneuvers described in the text. Individual source transits are observed as peaks marked by lower-case letters and are discussed in the text. The width of the individual peaks reflects the angular width of the detector field of view and the instantaneous rate of scan.

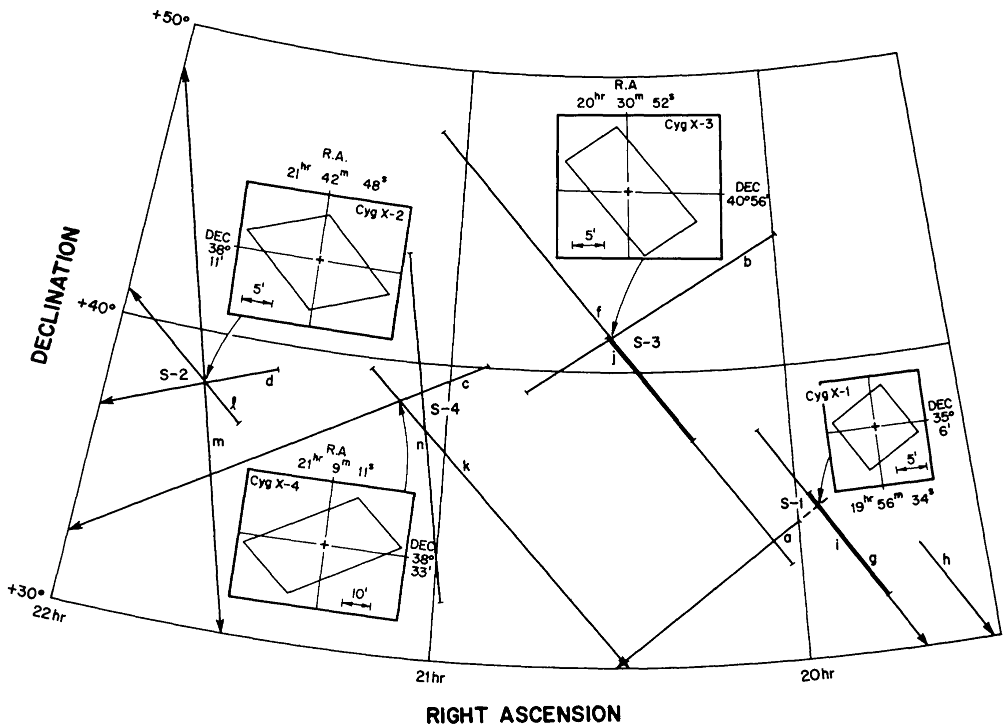

FIG. 3.—The lines of position as determined by each individual peak in the counting rate data are shown on the celestial sphere. The lower-case letters show the correspondence to the peaks in Fig. 2. The ratio of counts in the detectors $(A + C)$ to $(B + D)$ restricts the length of the line. As shown, the length includes $\pm 1\sigma$ uncertainty as determined by the counting statistics and a possible 2° systematic error due to differences in counter efficiency. Arrows indicate lines which continue somewhat beyond the diagram. Intersections between lines representing counting rate peaks of comparable intensity determine the location of the four sources shown. Enlargements of the intersection region show the actual location and the associated error box.

in mind the possibility that a weak source may be masked by a strong source. On this basis, the fourteen lettered peaks have been reduced to five sources, as shown in Figure 3, and discussed in the following paragraphs. For convenience, we denote the sources as S-1, S-2, etc.

S-1: This source is at the intersection of lines *a*, *g*, and *i*. The greater intensity of peaks *g* and *i* in $(A + C)$ than in $(B + D)$ indicates a position south of scan line 2. Peak *e* is apparently also caused by S-1. It occurs during a time when the rocket made a transition from one maneuver to another and was undergoing a rapid excursion compared to the normal scan rates. The line of position corresponding to *e* was not as precise as the other lines and was not drawn.

S-2: This source is at the intersection of lines *d*, *l*, and *m*, a location that is consistent with peak *d* appearing in $(B + D)$ but not $(A + C)$.

S-3: This source is at the intersection of lines *b*, *f*, and *j*. The position is consistent with these three peaks being of comparable intensity in the two detectors. The doubling observed for peak *b* is a result of the source actually being traversed twice within a short time. As with *e*, this peak occurs at a time when the rocket was switching between

TABLE 1

POSITION AND INTENSITY OF OBSERVED X-RAY SOURCES

	R.A. (1950)	Decl. (1950)	l^{II}	b^{II}	Intensity*	Intensity†	AS & E Designation	Corresponding Previous Designation
S-1........	$19^h56^m34^s$	35°6′	71.4	+ 3.1	0.46	3.0×10^{-9}	Cyg X-1	Cyg XR-1
S-2........	21 42 48	38 11	87.4	−11.3	.45	2.9	Cyg X-2	Cyg XR-2
S-3........	20 30 52	40 56	80.0	+ 0.7	.13	0.83	Cyg X-3	New source
S-4........	21 9 11	38 33	82.9	− 6.4	0.05	0.31	Cyg X-4	New source

* Counts cm^{-2} sec^{-1}, $2 < E < 5$ keV (corrected for electronic dead time and position within the field of view).
† Ergs/cm^{-2} sec^{-1}, $2 < E < 5$ keV, assuming an exponential power spectrum $I = I_0e^{-E/kT}$, $T = 5\times10^7$ ° K.

maneuvers and the motion was not steady. However, the star photographs allowed us to plot the motion in detail, and the line of position could still be drawn with only a slight loss of precision.

S-4: The small peaks *c*, *k*, and *n* appear to have a common intersection within the expected errors which we use to define this source. Its intensity is close to the limit of sensitivity of this survey. The peak *c* appears only in counters $(B + D)$ which is consistent with the source location. Peak *c* cannot be part of peak *b* (S-3), the correct shape of which can be seen in $(A + C)$. The peak *n* does not meet the 3σ requirement in each of the counters. At this time the rocket was beginning to re-enter the atmosphere, as shown by the decreasing background, so that the decrease in intensity is as expected. Peak *n* was not used to determine location. Alternate interpretations are possible for peaks for *c*, *k*, *n;* the interpretation that we have chosen is the simplest one that accounts for the data. It is possible to interpret these peaks in terms of more than one source located in the scan region. This implies that certain count rate peaks are missing from the data, either because the peak due to the source is obscured by the presence of a strong source, or that the peak does not meet the 3σ requirement.

S-5: This source shows up only as peak *h* in $(A + C)$. Since it does not appear in $(B + D)$ nor along scan line 1, it must be well south of scan line 2 and not consistent with being masked by peak *a*. It is apparently the result of a source outside the Cygnus region at around $l^{II} = 50°$ and observed earlier than 130 sec. These data will be discussed in a forthcoming paper.

The sources for which two or more intersections are obtained are listed in Table 1 along with their intensity and location, the location always being taken as the intersection of the two more precise lines of position. In each case the third line of position was consistent with the derived location. We also assign a name to each source in accordance with the nomenclature we first adopted in reporting X-ray sources in December, 1964 (Giacconi 1964). The size of the error boxes for each location was determined from the uncertainty in drawing the individual lines of positions. There are several sources of possible error, namely, the precision of the alignment between the camera and the X-ray fields of view, the knowledge of instantaneous orientation as found from the star photographs, and the determination of the exact time of transit of the X-ray source in the counters. The largest of these was the last. The actual transit time was found by fitting the measured response curve of the collimator to the observed data, and the error in transit time was determined from the χ^2 variation as the peak time was varied. In each case the several errors were combined in quadrature. We have considered the possible systematic errors which may affect this measurement. The largest systematic error that we can evaluate stems from the uncertainty in the laboratory measurement of the relative position of the field of view of the X-ray detectors with respect to the film plane of the aspect camera. If the spread between the several measurements that were made of this quantity is interpreted as a true displacement, rather than simply the random scatter around a mean value, we find that there may be present a 2 arc min systematic error. Accordingly, this amount was added directly to the uncertainties in drawing lines of position to give the resulting error boxes shown in Figure 3.

The source positions are shown in Figure 1 along with the results of earlier measurements carried out in the Cygnus region. Cyg X-1 and Cyg X-2 agree with earlier reported locations for X-ray sources in the region. We find the two to be of comparable strength, although of somewhat lower intensity than reported by Byram *et al.* (1966), who also find the two to be of near equal strength based on their April, 1965, flight. The source Cyg X-3, which is about $\frac{1}{3}$ the intensity of Cyg X-2 (we will discuss intensities relative to Cyg X-2 rather than Cyg X-1 which, as noted earlier, may be variable) has not been reported by either Byram *et al.* (1966) or Fisher *et al.* (1966).

We do not see Cyg A as an X-ray source. This object was traversed three separate times as shown in Figure 2. Summing the data from these transits yields a counting rate above background of 0.004 ± 0.01 cts cm^{-2} sec^{-1} in the 2–5 keV region. The upper limit (3σ) for the intensity of Cyg A is thus 0.03 cts cm^{-2} sec^{-1}, about $\frac{1}{15}$ of Cyg X-2. We also examined the data in the 5–7 keV energy range. We find a counting rate above background of $11 \pm 8 \times 10^{-3}$ cts cm^{-2} sec^{-1} in the region of Cyg A which is $\frac{1}{6}$ that observed from Cyg X-2 in the same energy range and consistent with zero. We conclude that our data are inconsistent with those reported by Byram *et al.* (1966), who report the X-ray emission from Cyg A to be about 0.4 of Cyg XR-2, the source that we denote as Cyg X-2. The earlier identification of Cyg A as an X-ray source was based on an unresolved peak adjacent to Cyg XR-1, which it may be possible to interpret in terms of a source at another location, perhaps Cyg X-3.

We do not see Cyg XR-4 or Vul XR-1. The former is reported to have an intensity $\frac{1}{3}$ Cyg XR-2, which we could not have failed to detect (cf. peaks *b*, *f*, or *j* in Figure 3 which correspond to the same relative intensity). Cyg X-4 is within the area of uncertainty of this source, but its intensity is found to be only $\frac{1}{9}$ of Cyg X-2. Vul XR-1 may be masked by Cyg X-1 on scan line 1 and too weak to be seen on scan line 3.

We turn now to the nature of the X-ray sources themselves. Only two sources have been positively identified with known visible or radio objects. One of these is the Crab Nebula, which was first identified as an X-ray source by Bowyer *et al.* (1964) on the basis of a lunar occultation observation. The X-ray emission region was found to be at least 2 arc min in diameter and centered with respect to the optical emission of the Crab by Oda, Bradt, Garmire, Spada, Sreekantan, Gursky, Giacconi, Gorenstein, and Waters (1967). The flux density (power per unit frequency) in both visible and radio exceeds that in X-rays by many orders of magnitude. The X-ray spectrum appears to obey a power law extending to at least 100 keV (Peterson, Jacobson, and Pelling 1966). The other identified X-ray source, Sco X-1 (Sandage *et al.* 1966) is found to be a blue, starlike object in which the flux density in the visible continuum is comparable to that found in X-rays, and which is not observed to be a radio source. The X-ray spectrum itself appears to be exponentially decreasing between about 2 and 40 keV (Peterson and Jacobson 1966).

Regarding the radio emission from the sources examined in this survey, we find that no radio source is listed in the 4C catalogue (Pilkington and Scott 1965) at the locations of Cyg X-1, Cyg X-2, and Cyg X-4 which puts a limit of about 2 MKS units (watts m^{-2} $(c/s)^{-1}$) for their radio emission at 178 Mc/s. This limit may be significant in the case of Cyg X-1, which is reported by McCracken (1965) (who also noted the lack of a radio source) and by Bleeker, Burger, Deerenberg, Scheepmaker, Swanenburg, and Tanaka (1967) to have a power-law X-ray spectrum extending to at least 60 keV, similar to that of the Crab Nebula rather than that of Sco X-1. However, the radio emission from the Crab Nebula is given as 1500 MKS units in the 4C catalogue; thus, Cyg X-1 is deficient in radio by almost three orders of magnitude compared to the Crab even though the object is weaker than the Crab in X-rays by only a factor of 2–3 at most.

Cyg X-3 lies directly along the projection of the Cygnus spiral arm as defined by the distribution of galactic hydrogen (Kerr and Westerhout 1965) and almost centered within the Cygnus X radio complex; however, it does not coincide with any one of the many individual radio sources into which this region has been resolved by Downes and Rinehart (1965). The object is within the small diameter ($\sim\frac{1}{2}°$) O association VI Cygni (Münch and Morgan 1953), which, if the coincidence is real, places Cyg X-3 at a distance of about 1500 pc. A possible connection between X-ray sources and O associations has been noted by O'Dell (1966). In view of the very heavy obscuration in this part of the sky (the extinction in front of one member of the VI Cygni association has been reported as being between 9 and 10 m by Morgan, Johnson, and Roman 1954), it may not be possible to attempt an optical identification. It is interesting to note in this connection that from a preliminary analysis of the data we find tentative evidence of a cutoff in the X-ray spectrum of this object at low energy that could be indicative of interstellar absorption of the X-rays.

There are a number of prominent objects in Cygnus that, a priori, were considered as possible candidates for X-ray emitters but that we do not observe as sources. In particular, we can set an upper limit on the X-ray emission from a number of old novae which were within our field of view. Regions containing P Cyg, Q Cyg, CP Lac, V404, DI Lac, and V450 were scanned with no detectable signal. To assess how meaningful our upper limits are, we have computed the expected X-ray intensity from these sources on the basis of their visual magnitude, assuming the ratio of X-ray to visible light outputs is identical to the one observed for Sco X-1. We then compare our upper limit with the expected value and we find that we observe $\frac{1}{50}-\frac{1}{6}$ of the computed intensity. Q Cygnus, for example, which was traversed at 182 sec and at 289 sec does not appear to be an X-ray source. Its emission in X-rays is less than $\frac{1}{200}$ of Sco X-1, while its visible light emission is about $\frac{1}{10}$ of Sco X-1; it is thus deficient in X-rays compared to Sco X-1 by a factor of 20. The data on the old novae were taken from Payne-Gaposchkin (1964).

However, the failure to observe X-rays from a given object as an X-ray source in the energy range 2–5 keV does not place a very significant limit on its X-ray emission at a slightly lower energy. If the sources are radiating by thermal bremsstrahlung, the high-energy end of the spectral distribution will be of the form exp $(-h\nu/kT)$; if, as suggested by Manley (1966), the X-rays represent the synchrotron radiation of a flat distribution of electrons with a high-energy cutoff, the high-energy end of the spectral distribution will be of the form $(\nu_c/\nu)^{1/2}$ exp $(-\nu/\nu_c)$, where ν_c varies as the square of the electron cutoff energy. At higher photon energies, where the exponential term becomes large, a small change in the properties (e.g., temperature or cutoff energy) of the X-ray source will have a substantial effect on the X-ray emission. We can, however, conclude that the temperature of the gaseous envelopes that are frequently invoked to account for the optical continuum in old novae cannot exceed 10^7 ° K.

We can summarize the results of this experiment as follows. Except for the observed X-ray sources and excluding small regions adjacent to the sources, there is no X-ray source in Cygnus as strong as $\frac{1}{100}-\frac{1}{200}$ of Sco X-1. In particular, neither Cyg A nor a number of the known old novae are observed to be X-ray sources. Furthermore, none of the X-ray sources is associated with even a very weak radio source; this includes Cyg X-3, which is in a region where the density of resolved radio sources exceeds $1/(\text{deg})^2$. Of the X-ray sources for which an optical search was made (as discussed in the accompanying paper) one, Cyg X-1, may be obscured optically; the other, Cyg X-2, is found to be associated with a visible object that is similar to Sco X-1. Thus, it would appear that Sco X-1 is not unique and with Cyg X-2 belongs to a class of celestial objects in which the dominant radiative energy loss is in the form of X-ray and which appear in visible light as blue star-like objects. These two X-ray sources were the only ones for which positions have been measured with sufficient accuracy to attempt a search for an optical counterpart (apart of course for the Crab Nebula) and which are not badly obscured. Thus, it must be presumed, on the basis of what we now know, that several of the other known galactic X-ray sources also belong to this same class.

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