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LMC X-1, X-2, AND X-3: PRECISE POSITIONS FROM THE *HEAO 1* MODULATION COLLIMATOR

M. D. JOHNSTON,* H. V. BRADT,* R. E. DOXSEY,* H. GURSKY,† D. A. SCHWARTZ,†
J. SCHWARZ,† AND J. VAN PARADIJS*‡

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ABSTRACT

We report precise (~20″) positions for the Large Magellanic Cloud X-ray sources LMC X-1, X-2, and X-3 determined with the *HEAO 1* scanning modulation collimator. The error regions for LMC X-1 and X-3 contain, respectively, the B5 supergiant R148 and a possibly variable B III–IV star. Spectra taken of the latter confirm the spectral type and show that it is a member of the LMC. We have searched for a previously reported extended component of LMC X-1 and obtain upper limits which exclude it.

Subject headings: galaxies: Magellanic Clouds — X-rays: sources

I. INTRODUCTION

There are known to be at least seven X-ray sources in the direction of the Large Magellanic Cloud (Leong *et al.* 1971; Rapley and Tuohy 1974; Markert and Clark 1975; Delvaille 1976; Schnopper and Delvaille 1977; Griffiths and Seward 1977; White and Carpenter 1978). Of these, only LMC X-4 has a firmly established optical counterpart (Sanduleak and Philip 1976; Chevalier and Ilovaisky 1977; White and Davidson 1977; Li, Rappaport, and Epstein 1978). The identification and study of the optical counterparts of these sources are of great interest, since most sources of such high luminosity ($\gtrsim 10^{38}$ ergs s^{-1}) in the Galaxy are located in heavily obscured regions in the disk of the Galaxy or toward the galactic center. The relatively low obscuration in the LMC ($A_v \lesssim 1$ mag; Feast, Thackeray, and Wesselink 1960) makes optical observations promising.

We present here precise positions for LMC X-1, X-2, and X-3 determined with the scanning modulation collimator on *HEAO 1* during its first 3 months of operation. The measurements reported here reduce the positional uncertainty of these sources by a factor of as much as 8 over the best previously reported results. LMC X-1 is of particular interest, since Epstein (1977) has reported evidence for an extended X-ray component and suggests a supernova remnant model for the source. We have searched for an extended component and place stringent upper limits on emission from an extended region with angular size greater than 30″ full width at half-maximum (FWHM).

II. OBSERVATIONS AND RESULTS

The *HEAO 1* scanning modulation collimator (Gursky *et al.* 1978) consists of two four-grid modulation collimators of FWHM 30″ (MC1) and 120″ (MC2), respectively, with overall fields of view restricted to 4° × 4° FWHM. During normal scanning operation the instrument's field of view sweeps out a band 90° away from the Sun. The Large Magellanic Cloud is located very near the south ecliptic pole and a portion of it is thus in the experiment field of view every orbit.

Celestial locations were determined from the analysis of ~700 orbits of data taken over the period 1977 August 15–November 15. For each source we obtained lines of position from each collimator by superposing the data in independent sets of 20–70 orbits (Fig. 1). Only those data taken when the source was within ±2° of the scan circle were used in these sums, which totaled 200–350 orbits for each source. The significance of the detection in each sum varies from 3 to 30 σ, yielding 1 σ positional errors of 7″–20″. The rms distance of each line from the most probable source location is less than or equals 7″. The lines of position for each source intersect at angles as great as 40°–75° due to the rotation of the scan circle as the Sun moves along the ecliptic.

The most probable positions and error regions are given in Table 1. These results are compared with those of previous observations in Figure 1. Finding charts showing the *HEAO 1* error regions have been prepared from the ESO (B) Sky Survey negatives (Fig. 2 [Pl. L1]). The error regions are the rectangles circumscribing the 90% confidence ellipses obtained by combining the separate lines of position for each source. The confidence interval includes contributions from photon-counting statistics as well as systematic errors in the aspect determination and collimator alignment.

We have searched for extended emission from all three sources by superposing the data about the most probable position and fitting for both point and extended components. For the extended component we used a Gaussian surface-brightness distribution. The collimator point source response was determined from scanning observations of several bright identified galactic sources (e.g., Fig. 3*a*). It differs from the single-scan point response function due to orbit-to-orbit aspect errors which are well modeled by a Gaussian distribu-

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* Center for Space Research, Department of Physics, Massachusetts Institute of Technology.

† Harvard-Smithsonian Center for Astrophysics.

‡ On leave from the Astronomical Institute, University of Amsterdam.

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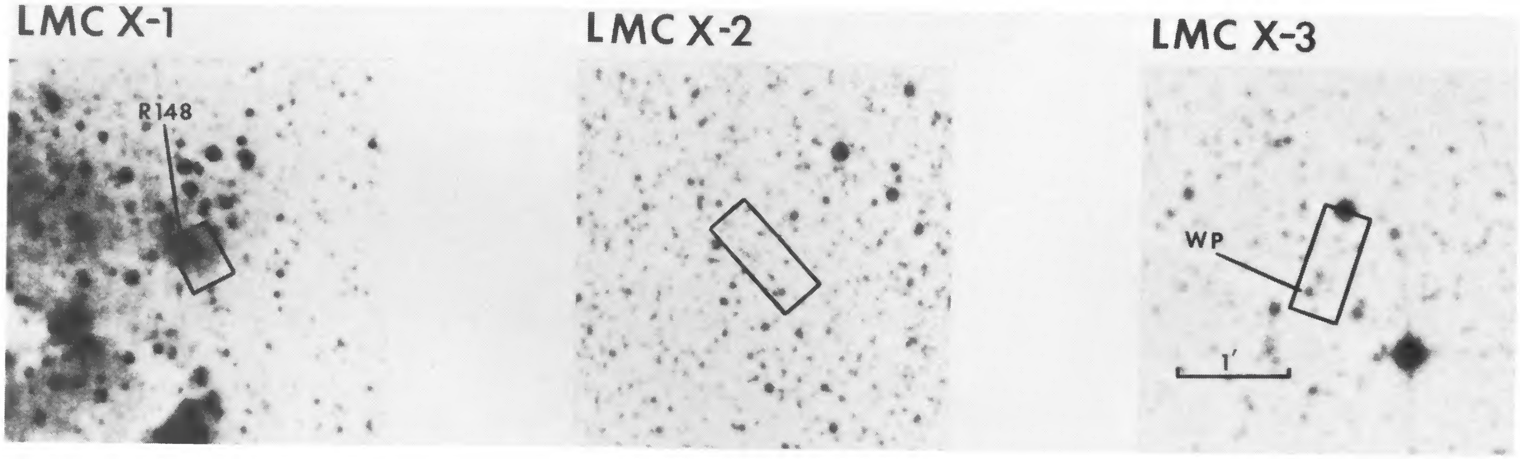

Fig. 2.—Finding charts for (*a*) LMC X-1, (*b*) X-2, and (*c*) X-3 prepared from the ESO (B) Sky Survey negatives showing the *HEAO 1* error regions. The corners of the error regions are given in Table 1. Previously suggested candidates which are consistent with the *HEAO 1* positions are indicated for LMC X-1 and LMC X-3 (Jones, Chetin, and Liller 1974; Rapley and Tuohy 1974; Warren and Penfold 1974, 1975).

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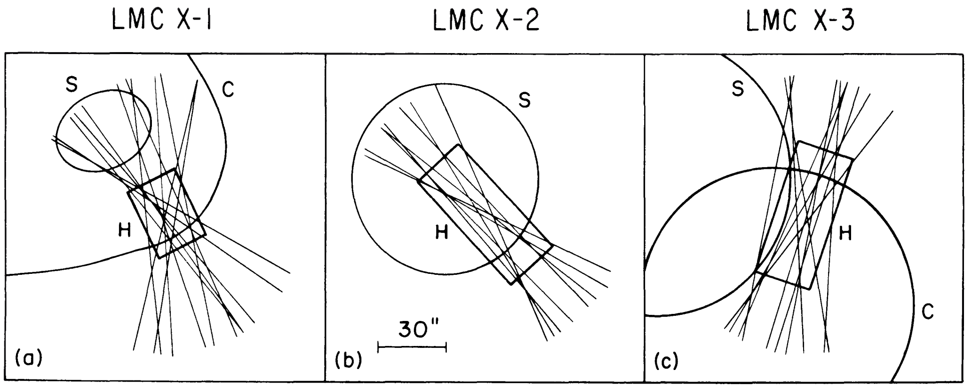

FIG. 1.—*HEAO 1* lines of position and error regions for (*a*) LMC X-1, (*b*) X-2, and (*c*) X-3 compared with the results of previous observations. C, *Copernicus* (Rapley and Tuohy 1974); S, *SAS 3* (Schnopper and Delvaille 1977; Epstein 1977); H, *HEAO 1* (this *Letter*). Each line is the result of the superposition of 20–70 orbits of data taken at different times over the period 1977 August 15 to November 15. The 1 σ errors on each line range from 7″ to 20″. The scale for all three diagrams is indicated in (*b*).

TABLE 1

CELESTIAL POSITIONS OF LMC X-1, X-2, AND X-3

	Position (epoch 1950.0)	90% Confidence Error Region*			
LMC X-1..........	$5^h40^m04^s.8$, −69°46′09″ 85°.0202, −69°.7691	19″ N 3 W	8″ S 18 W	19″ S 3 E	8″ N 18 E
LMC X-2..........	5 21 19.0, −72 00 07 80°.3292, −72°.0020	30 N 12 E	14 S 30 W	30 S 12 W	14 N 30 E
LMC X-3..........	5 38 38.1, −64 06 20 84°.6587, −64°.1055	24 N 21 W	32 S 3 W	24 S 21 E	32 N 3 E

* The corners of the error regions are given as offsets in seconds of arc from the most probable position.

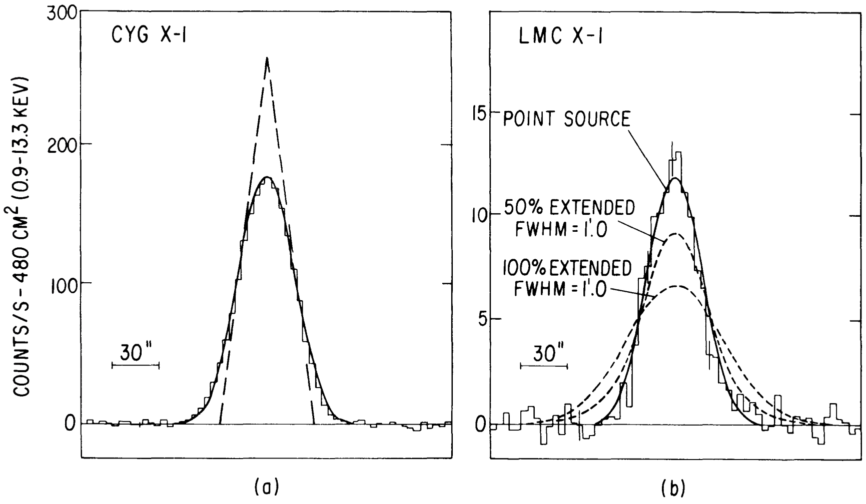

FIG. 3.—(*a*) The MC1 single-scan point source response (*dashed line*) compared with the superposition of 109 orbits of data for Cyg X-1. Orbit-to-orbit aspect variations are well molded by a Gaussian distribution with a standard deviation of 12″ folded with the single-scan response (*solid line*). (*b*) The superposition of 314 orbits of data for LMC X-1 compared with the expected point source response shown in (*a*). Also shown are the expected counting rates for a source consisting of a 50% and 100% extended component of FWHM 1′.0 (*dashed lines*). All three curves are normalized to the same total flux, which is consistent with that measured in MC2.

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tion with a standard deviation of 12″. Confidence intervals for the size and extended component fraction were determined with the method of Lampton, Margon, and Bowyer (1976).

We find no evidence for finite extent: the best-fit model for all three sources consists of a point source only (e.g., Fig. 3*b*). We place limits (90% confidence) on an extended component of size 0ʹ.5–9ʹ.5 (FWHM) of 15%, 25%, and 40% of the total fluxes of LMC X-1, X-2, and X-3, respectively. The time-averaged total flux densities, assuming a Crab-like spectrum, are 18, 16, and 5 μJy (averaged over 0.9–13.3 keV; 1.0 μJy = 0.242×10^{-11} ergs cm^{-2} s^{-1} keV^{-1}), with uncertainties of ~30%. These correspond to luminosities of 1.9×10^{38}, 1.7×10^{38}, and 5.4×10^{37} ergs s^{-1} at 55 kpc (Bok 1966).

III. DISCUSSION

a) *LMC X-1*

LMC X-1 is located in the direction of the emission nebula N159F (Henize 1956) within the stellar association LH 105 (Lucke and Hodge 1972). The possibly extended radio source MC 77 (McGee, Brooks, and Batchelor 1972) lies 1ʹ.6 east of the *HEAO 1* position. LMC X-1 is also located within the error region for the infrared source GL 4056 (Price and Walker 1976).

The brightest star in the *HEAO 1* error region is R148 (CPD −69°474), cataloged by Feast *et al.* as type B5 I. Their spectrum showed the presence of Hα in emission which they concluded originated in the surrounding nebula. R148 was one of several candidate stars proposed independently by Jones, Chetin, and Liller (1974) and by Rapley and Tuohy (1974).

Photometric observations of R148 have been reported by Jones, Chetin, and Liller (1974), Isserstedt (1975), Dufour and Duval (1975), and Warren and Penfold (1975). The mean of all reported observations gives $V = 12.02$, $U - B = -0.57$, $B - V = +0.24$, with no evidence for variability. R148 is the most reddened star reported in either Cloud: $A_v = 0.96$ mag (Feast *et al.*). We assume a distance to the LMC of 55 kpc (Bok 1966) to obtain $M_v = -7.6$.

Epstein (1977) has reported that LMC X-1 consists of an extended component with FWHM 1ʹ.3 ± 0ʹ.3 contributing at least 60% of the flux observed with *SAS 3* in 1976 February. The *SAS 3* RMC and *HEAO 1* MC proportional counter systems differ in effective area but have very similar spectral responses. We assume that the spectrum of LMC X-1 has not changed significantly between the two observations, and by comparing the *HEAO 1* counting rates with those reported by Epstein (1977), we conclude that LMC X-1 was brighter by a factor of 1.5 ± 0.1 during the *HEAO 1* observation. The upper limits we obtain on an extended component are 15% and 20% of the *HEAO 1* flux at 90% and 95% confidence, respectively, and amount to about 22% and 30% of the *SAS 3* flux.

We conclude that LMC X-1 is a compact source probably associated with one of the stars in the vicinity of the nebula N159F. The B5 supergiant R148 is a possible candidate, although optical observations of other stars in the error region are difficult and have yet to be undertaken. Galactic sources which have been identified with OB supergiants typically have much harder spectra than LMC X-1 (see Jones 1977; Markert *et al.* 1977), but it is uncertain whether this is an essential feature of this type of X-ray binary.

If LMC X-1 is located within the nebula it would be unique among luminous X-ray sources. Only two galactic H II regions have been associated with X-ray sources: the Orion Nebula (Giacconi *et al.* 1974; den Boggende *et al.* 1978; Kelley and Bradt 1978; Kelley *et al.* 1978) and η Carinae nebula (Seward *et al.* 1976). These may belong to a different class of X-ray sources, since their X-ray luminosities are at most 10^{-4} that of LMC X-1 if the nebular associations are correct. The age dispersion of young star clusters in the LMC has been shown to be at least as great as 10^7 years (Westerlund and Smith 1964). Thus, as noted by Rapley and Tuohy (1974), the location of LMC X-1 does not contradict current understanding of the evolution of an X-ray binary which is thought to take at least 10^7 years (see, e.g., Kraft 1973).

The existence of a high-luminosity X-ray source in such a nebula could contribute significantly to the energetics of the system. At X-ray energies above 1 keV the dominant absorption mechanism would be photoionization of elements with $Z \geq 6$. The resulting photoelectrons would contribute to nebular heating and ionization. N159F was one of a number of LMC H II regions studied spectroscopically by Dickel (1964). She assumed an electron temperature of 10^4 K and derived from the Hβ line strength and isophotes a central electron density of 100 cm^{-3} and a radius of 11 pc. To estimate the X-ray absorption in such a nebula, we assume a thermal bremsstrahlung spectrum with $kT = 2.7$ keV for LMC X-1 (Markert and Clark 1975) and the absorption cross sections given by Brown and Gould (1970). About 5% of the 1–10 keV X-ray flux absorbed in the nebula would be reemitted as recombination line radiation, while the remainder would contribute to nebular heating through Auger transitions (Fink *et al.* 1966). This would amount to about 10^{37} ergs s^{-1} and is comparable to the Lyman continuum emission of a late O-type star (Churchwell and Walmsley 1973). However, the low metal abundance in the LMC (see Clark *et al.* 1978 and references therein), if verified for N159F, would reduce the possible X-ray heating by a factor of as much as 4 to 10. Optical, infrared, and radio studies of this nebula at high spatial resolution would be useful in searching for possible effects of such X-ray heating.

b) *LMC X-2*

LMC X-2 is located south of the bar of the LMC in a region relatively sparsely populated with stars. The only previously proposed candidate in the LMC is the supergiant R96 (Jones, Chetin, and Liller 1974; Rapley and Tuohy 1974). This star is excluded since it falls well outside the *SAS 3* (Schnopper and Delvaille 1977) and *HEAO 1* error regions. For the brightest star near the *HEAO 1* error region (near the eastern corner in Fig. 2*b*), we estimate $B = 17$ from the image diameter

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on the ESO print. If the source is in fact located in the LMC, then the optical counterpart can be no more luminous than $M_v = -2$.

c) LMC X-3

Warren and Penfold (1974, 1975) have performed *UBV* photometry on all stars brighter than $V = 17$ in the *Copernicus* LMC X-3 error circle (Rapley and Tuohy 1974). Their favored candidate, indicated in Figure 2*c*, is consistent with the *HEAO 1* position. For this star they measured $V = 16.9$, $B - V = -0.06$, $U - B = -0.66$. They report evidence for brightness variation ($\sim$0.1 mag) on a time scale of days, and conclude that the star is a probable member of the LMC and is type OB, luminosity class III–IV.

Optical spectrograms of the two brightest stars in the LMC X-3 error box have been taken with the 3.6 m telescope at the European Southern Observatory. The Boller and Chivens Cassegrain spectrograph was used in conjunction with the Carnegie image tube. The spectrograms were taken on IIa-O (baked) plates and cover the wavelength range from $\sim$3700 to $\sim$5200 Å with a dispersion of 60 Å mm^{-1}. Density tracings were made with the Faul-Coradi microphotometer of the Astronomical Institute of Utrecht.

The spectrum of the brighter star near the northern edge of the *HEAO 1* error box (Fig. 2*c*) was taken 1978 March 7.0 (UT). It shows (in absorption) relatively strong hydrogen lines, strong Ca II H and K lines, a weak G band, and numerous weak metallic lines. We classify it as a late F-type star. The spectrum of the candidate suggested by Warren and Penfold (1974) was taken 1978 March 8.0 (UT). Absorption lines of hydrogen and He I are clearly visible, but there is no trace of the He II λ4686 line. This indicates spectral type B for this star.

The F-type star has a small radial velocity ($V_{\rm rad} = 25 \pm 10$ km s^{-1}), whereas the B star has a large radial velocity ($V_{\rm rad} = +400 \pm 70$ km s^{-1}, based on Hγ and Hδ). Since no radial-velocity standard stars were observed, these values may contain a systematic zero point error (very probably ≤ 50 km s^{-1}). However, the large positive radial velocity of the B-type star shows that it is certainly a member of the LMC ($V_{\rm rad} = +270$ km s^{-1}; Feast *et al*).

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H. V. Bradt, R. E. Doxsey, M. D. Johnston, and J. van Paradijs: Center for Space Research, Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139

H. Gursky, D. A. Schwartz, and J. Schwarz: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

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