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OPTICAL COUNTERPARTS OF THE LARGE MAGELLANIC CLOUD X-RAY POINT SOURCES

A. P. COWLEY[1]
Department of Physics, Arizona State University
D. CRAMPTON[1] AND J. B. HUTCHINGS[1]
Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics
D. J. HELFAND[2] AND T. T. HAMILTON
Columbia Astrophysics Laboratory
J. R. THORSTENSEN[1]
Department of Physics and Astronomy, Dartmouth College
AND
P. A. CHARLES[1]
Department of Astrophysics, University of Oxford
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ABSTRACT

The results of an optical identification program for X-ray point sources in the direction of the Large Magellanic Cloud are presented. With the addition of the new identifications, 22 of the 24 point sources with accurate ($\sim 3''$) positions obtained with the *Einstein Observatory* HRI are now identified. These include 13 foreground stars, three background active galaxies, and six LMC members (LMC X-1, LMC X-2, LMC X-3, LMC X-4, A0538−66 and Columbia Astrophysics Laboratory [CAL] 83) which are known or suspected to be binaries. The 24 other sources in the *Einstein* LMC survey have only IPC ($\sim 30''$) positions and on average are less luminous and in more crowded regions of the LMC. Two are probably identified (both with active galaxies), and promising candidates have been found for about half of the remainder. The candidates proposed for sources CAL 8, CAL 9, and CAL 37 are probable X-ray binaries in the LMC. On the basis of our new identifications, comparisons are made between the overall stellar X-ray population in the LMC and in the Galaxy. Although the mean X-ray luminosity of the LMC sources is significantly higher than that in the Galaxy, the total number of stellar X-ray systems per unit mass is similar in the LMC and the Galaxy.

Subject headings: galaxies: Magellanic Clouds — galaxies: stellar content — X-rays: binaries — X-rays: sources

I. INTRODUCTION

The four bright binary sources (LMC X-1, LMC X-2, LMC X-3, and LMC X-4) in the Large Magellanic Cloud (LMC) were among the first extragalactic X-ray sources to be identified. Prior to launch of the *Einstein Observatory*, however, they and the transient A0538−66 (also known as 0535−66) were the only sources known in the Cloud. The Columbia Astrophysics Laboratory (CAL) devoted a significant fraction of its *Einstein* program to a systematic soft X-ray survey of the LMC. Early results revealed a large number of new sources, including virtually all of the known optical and radio supernova remnants (SNR) (Long and Helfand 1979; Helfand and Long 1980; Helfand 1982). A preliminary analysis of the entire survey consisting of 103 imaging proportional counter (IPC) observations covering ~ 37 deg^2 yielded a catalog containing 97 sources in the direction of the LMC (Long, Helfand, and Grabelsky 1981, hereafter LHG). By far the largest class of identified objects in the catalog was composed of (25) SNRs (Mathewson *et al.* 1983). Apart from a few candidate foreground stars and the original four binary systems, however, the other ~ 60 sources remained unidentified.

In order to increase the identified fraction of the survey and to study the extended sources in greater detail, a program of high-resolution imager (HRI) pointings was undertaken by CAL and a number of guest investigators including many of the present authors. Here we collect all of these observations which provide $\sim 3''$ spatial accuracy over 25′ diameter fields of view in the 0.3–3.0 keV band (Giacconi *et al.* 1979). At the same time, a program of optical identification was initiated, using ground-based spectroscopy, photometry, and objective prism data. The aim of the present work was to identify optically all of the point sources and to study them in sufficient detail so that meaningful comparisons could be made between the X-ray source population in the LMC and that in other galaxies. It is of particular interest to determine whether the kinds of X-ray emitting objects and their physical properties are the same in different host galaxies where the mean metallicity, stellar density, and age are quite different. Below, we discuss, in turn, the X-ray (§ II) and optical (§ III) observations and their analysis. In § IV, we examine the observed and expected numbers of foreground and background X-ray emitters superposed on the LMC, while in § V we discuss the Cloud members.

II. THE X-RAY DATA

All of the HRI data presented here have been processed with the final reduction algorithms which, among other improvements to the original analysis, provides point source positions with systematic uncertainties of less than 3″.5. Figure 1 is a

[1] Visiting Astronomer, Cerro Tololo Inter-American Observatory, which is operated by AURA, Inc., under contract with the National Science Foundation.
[2] Alfred P. Sloan Fellow.

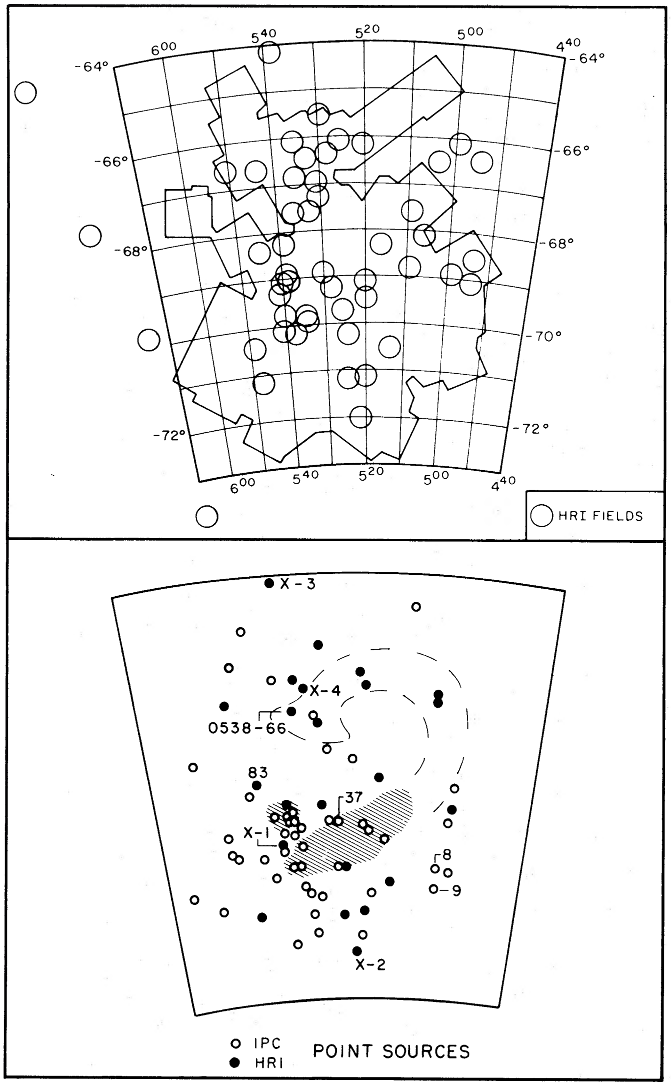

FIG. 1.—Distribution of LMC X-ray coverage and point sources. *Upper*, IPC coverage is outlined by straight edges, and HRI fields are shown by circles. *Lower*, detected point sources in the LMC, shown at the same scale as the upper figure. The definite LMC binaries are labeled. The Bar and 30 Doradus region are shown by cross-hatching; a faint arm of hot stars is also sketched in with a dashed line.

reproduction of the IPC coverage map and source locations from LHG on which we have superposed circles corresponding to the HRI pointings and have also indicated the detected point sources. The targets of those HRI pointings which fall outside the original survey area are globular clusters and previously known binaries or optical supernova remnants. A total of 48 out of the original 97 IPC sources were included in at least one HRI field.

All 71 HRI fields were searched for pointlike sources of X-ray emission using an algorithm with a detection threshold designed to find $\lesssim 1$ false source per field. The list of sources generated was edited by eliminating all those which fell within regions of diffuse emission (i.e., SNRs) and those for which the total number of source counts within a 32″ square was less than 3.5 σ above the local (2′ square) background. The final list of 24 sources whose spatial distribution is consistent with the point response function of the HRI ($\sim 8''$ FWHM for an on-axis source with a spectrum characterized by $kT \sim 1$ keV) is given in Table 1. Position errors quoted are 90% confidence error circle radii and include both statistical uncertainties and a $3''.5$ systematic error summed in quadrature. HRI count rates are background subtracted and include corrections for instrument dead time, telescope vignetting, the detector quantum efficiency, and the fraction of source counts scattered outside the central response function peak. Nineteen of these sources appear in the catalog of LHG. The IPC count rates are listed in the fifth column. Upper limits to the IPC rates are also included for the three sources (A, B, and G) which fell within the original survey region but which were not detected in those earlier observations. The IPC/HRI ratio for each source is given in the last column. This ratio is a strong function of a source's spectrum, ranging from ~ 2 for the softest sources with little or no interstellar absorption to more than 50 for those with highly cutoff, hard spectra. The fact that many of the detected HRI sources have ratios of less than 2 implies substantial variability such as that evident in the range of HRI flux values for the three objects (49, 69, and G) observed at several epochs. The very high ratio for source 24, which has a moderately soft IPC spectral parameter of -0.3 (LHG), provides similar evidence of variability for this object. Based on these data plus the multiple IPC exposures reported in LHG, we indicate in the sixth column those sources which show evidence of significant (greater than a factor of ~ 2) flux changes on the time scale of months to years. Seventeen of the 24 sources detected in the HRI are seen to be variable, confirming their point source designation.

In Table 2 we list the remaining 24 sources from LHG which had fluxes of greater than 0.02 IPC counts s^{-1} and are not confirmed SNRs. Positions quoted are the best available and are dominated by systematic uncertainties of $\sim 30''$. Thirteen of these sources fell within HRI fields but were not detected. Limits on the HRI count rates were established by finding the 32″ box within 2′ of the IPC position which had the largest background-subtracted count rate; the quoted point source limit (fifth column) is this maximum rate plus 3 σ. Upper limits on diffuse emission were determined by summing the counts within a $2'.2$ region (35 pc at the LMC) centered on the IPC position and subtracting a mean field background. Quoted limits are this background-subtracted rate plus 3 σ. In four cases (sources 17, 27, 48, and 60), evidence of diffuse emission was found at greater than 3 σ significance; radio and optical observations are underway to confirm these sources as SNRs.[3] At least nine of the IPC sources are variable (LHG), establishing that these are true point sources.

The 48 sources of Tables 1 and 2 comprise all possible point X-ray sources with 0.2–4 keV fluxes greater than 5×10^{-13} ergs cm^{-2} s^{-1} known in the direction of the LMC. This list forms the basis for the optical identification program which forms the bulk of the work reported here. The X-ray survey of LHG is complete within the 37 deg^2 area outlined in Figure 1 to a flux limit of 0.032 IPC counts s^{-1} ($\sim 8 \times 10^{-13}$ ergs cm^{-2} s^{-1}). A total of 52 sources were detected above this limit, of which 18 are confirmed SNRs and 22 others are identified below. Optical counterparts for the remaining 13 sources are constrained by the data presented in § III and through a

[3] After this article was submitted, sources 27 and 48 were confirmed as SNRs by B. Y. Mills, D. S. Mathewson, and collaborators, as was IPC source 20 (Table 2) and source 62 from LHG. All remain here as "candidate SNRs" in the discussion and the tables.

TABLE 1

HRI SOURCES IN THE DIRECTION OF THE LARGE MAGELLANIC CLOUD

Source Number	X-ray Position (1950.0)				Count Rates (ct s) HRI		IPC		Var.?	IPC/HRI (ratio)
6	$04^h58^m56.91^s$	$\pm0.60^s$	$-68°55'23.0''$	$\pm3.4''$	0.021	±.005	0.032	±.007	V	1.5
E[a]	05 02 46.58	0.91	-66 30 32.4	5.4	.014	±.004	----	---		---
F[a]	05 02 59.87	1.55	-66 37 56.0	9.2	.022	±.006	----	---		---
18	05 13 32.09	0.71	-70 31 09.7	3.9	.020		.032	±.005	V	1.6
20	05 16 18.79	0.69	-68 18 51.7	3.9	.023	±.002	.046	±.011	V	2.0
24	05 19 43.01	1.05	-71 07 02.1	5.4	.0015	±.0006	.052	±.006	V	35.
A[a]	05 19 52.42	1.22	-66 16 51.1	7.2	.012	±.0035	(.014	±.006)	V	1.2
28	05 20 08.65	0.78	-66 07 20.9	4.5	.011	±.003	.038	±.006		3.5
30	05 21 16.78	0.76	-72 00 22.7	3.5	1.3	±.03	8.28	±.07	V	6.4
32	05 24 31.94	0.71	-70 13 45.1	3.9	.013	±.0036	.029	±.007	V	2.2
33	05 24 41.25	0.61	-71 12 12.9	3.4	.088	±.009	.18	±.012	V	2.1
42	05 28 36.03	0.60	-65 29 12.7	3.4	2.03	±.020	.61	±.03	V	0.3
43	05 29 44.37	0.70	-68 54 21.6	3.9	.012	±.0035	.043	±.008		3.6
B[a]	05 30 53.82	1.41	-67 08 03.5	8.2	.001	±.0003	<.014	---		<14
49	05 32 48.08	0.58	-66 24 14.1	3.0	.025 to .61[b]		---	---	V	---
57	05 35 20.11	1.04	-66 14 44.2	6.3	.004	±.0015	.014	±.005		3.5
G[a]	05 35 43.2	0.60	-66 53 37.6	3.4	.015 to .12[b]		<.010	---	V	0.08-0.67
69	05 38 39.38	0.70	-69 25 10.8	5.0	.013 to .079[b]		.069	±.004	V	0.9 -5.3
70	05 38 40.24	0.60	-64 06 34.1	3.4	6.3	±.05	---	---	V	----
71	05 38 53.42	0.60	-68 54 41.6	3.4	.027	±.003	.034	±.004	V	1.3
78	05 40 06.06	0.70	-69 46 02.2	4.0	1.40	±.03	10.3	±.08	V	7.4
83	05 43 48.38	0.61	-68 23 34.1	3.4	.17	±.013	.16	±.04	V	0.98
87	05 47 26.8	3.	-71 09 50	10.	.033	±.006	.044	±.006	V	1.3
91	05 50 34.04	0.93	-66 37 40.0	5.4	.003	±.001	.044	±.007		15.

[a] Sources not detected in the original IPC survey of LHG are designated by letters A–G (letters C and D were for marginal HRI detections which do not appear in the reprocessed HRI data and are thus not included here).

[b] Range of fluxes recorded in observations separated by many days; positions are averages from several determinations.

COMMENTS.—Source 6: $U-B$ colors in Table 3 are obviously influenced by emission lines of H and Ca II. SIT spectrum: 1982 Feb; image-tube spectrum: 1983 Nov. Source shows evidence of X-ray variability by a factor of >2 on a time scale of months from (*a*) data reported by LHG, (*b*) multiple HRI pointings reported here, and (*c*) an IPC/HRI ratio grossly inconsistent with its IPC spectrum.

Source E: A close double is at the X-ray position; each star is $m_V \sim 14.5$. The southern component is an O9 V star in the LMC; the northern star is a Ba II star with strong C_2 bands. The S component seems the more likely identification.

Source F: Direct plates also show that the object is a galaxy.

Source 18: Spectral type from 47 Å mm^{-1} plate: 1982 Feb; finding chart: Sanduleak and Philip 1977, star 30-11; $\Delta m = 0.8$ mag (Hodge and Wright 1967); *R* plate taken.

Source 20: Spectral type from two 47 Å mm^{-1} plates: 1982 Nov; color more consistent with G7 V.

Source 24: *U*, *B*, *R* plates taken; finding chart given in this paper. The image is elongated, with the dMe star being the brighter, northern component with a magnitude of ~15.5. The southern component is much fainter but appears to be UV bright.

Source A: Spectral type from two poor 47 Å mm^{-1} plates: 1982 Nov; color suggests G8 V.

Source 30: Blue continuum with He II λ4686 emission (Pakull and Swings 1979); radial velocity suggests it is probably an LMC member with $M_B \sim -1$.

TABLE 1—*Continued*

Source Number	LMC Member?	Suggested Optical Identification	m_B	Comments	Footnotes
6	no	dK5e	13.6		*
E[a]	yes?	O9V	~14	north of pair; i.d. not certain	*
F[a]	no	Seyfert gal.		Z=0.064; very broad H em; strong FeII em.	*
18	no	V12567	15.0	dM4e;H, CaII emission	*
20	no	G1V	11.4		*
24	no	dMe	~15	H, CaII em	*
A[a]	no?	G5V:	10.9		*
28	no	G8V	11.8	Houk (1982) gives G6/8V	
30	yes	pec.em. star	~18v	LMC X-2	*
32	no	ft. Seyfert gal.	~20	Z=0.15	*
33	no	dM5e	14.3	strong H,CaII emission; Be577	*
42	no	HD36705	7.3	K1IIIp; weak CaII em?; RS CVn?	*
43	no	G2III/IV	10.2		*
B[a]	no?	late dK:		identification uncertain	*
49	yes	O8III	13.9	LMC X-4; $P=1.4^d$; neutron star companion	
57	no	dM4e	~14	H, CaII emission	
G[a]	yes	star "Q"	15.7	Be pec (var); 0535-66 is 16 day X-ray transient	*
69	no	dK7e	13.4	H, CaII emission	*
70	yes	B3V	~16.5v	LMCX-3, $P=1.7^d$; black hole secondary	*
71	no	G2V		weak CaII emission?	*
78	yes	O8V or B5I	14.5 or 12.5	LMC X-1; uncertain which star is X-ray source	*
83	yes	pec.em. star	~16.8	blue continuum + HeII em. (var.)	*
87		-------		several faint blue stars in field: more data needed	
91	no	Seyfert gal.		Z = 0.076	*

Source 32: Spectrum and redshift obtained at AAT: 1983 Jan; *U*, *B*, *R* plates taken; finding chart given in this paper.

Source 33: Finding chart for BE 577: Bohannan and Epps 1974. Star is also S162 (Henize 1956) and Sanduleak and Philip 1977, star 48-8; image-tube spectrum: 1981 Feb; low (galactic) radial velocity.

Source 42: Spectral type from Houk and Cowley 1975; 47 Å mm^{-1} plate (1982 Nov) gives G8 IV/V.

Source 43: Both SIT vidicon (1982 Feb) and 47 Å mm^{-1} image-tube spectrogram (1982 Nov) were used to determine spectral type.

Source B: SIT vidicon spectrum (1982 Nov) of star a few arcsec NW of X-ray position is late K, but faintness of star makes identification uncertain; *U*, *B*, *R* plates taken; finding chart given in this paper.

Source G: Called both 0535−66 and 0538−66; $P = 16.5$ days (Charles *et al.* 1983); finding chart: Johnston, Griffiths, and Ward 1980.

Source 69: 47 Å mm^{-1} spectral plate: 1982 Feb.

Source 70: Orbital parameters given by Cowley *et al.* 1983.

Source 71: SIT vidicon spectra: 1982 Nov.

Source 78: The X-ray position lies between R148 and #32 (Cowley, Crampton, and Hutchings 1978; Pakull 1980), which is 5″ away. The latter star has an orbital period of ~4 days; if it is the X-ray source, the companion may be a black hole (Hutchings, Crampton, and Cowley 1983).

Source 83: Numerous spectroscopic observations show that the velocity and spectrum are variable with a probable period near a week; *U*, *B*, *R* plates taken; finding chart given in this paper.

Source 91: *U*, *B*, *R* plates taken; finding chart given in this paper. Cristiani and Tarenghi 1984 give details of this Sy 1 galaxy.

TABLE 2

IPC SOURCES IN THE DIRECTION OF THE LARGE MAGELLANIC CLOUD

Source Number	X-ray Position (1950.0)		Count Rates (ct s) IPC		HRI(pt.)	HRI(ext.)	IPC/HRI Point Source	Extended
8	$05^h01^m06.6^s$	$-70°08'52''$	0.039±	.012	----	----	----	----
9	05 01 50.8	-70 37 52	.024	.005	----	----	----	----
15	05 09 31.7	-69 11 25	.032	.006	----	----	----	----
17	05 10 59.7	-68 48 34	.028	.005	<0.002	0.005±.0015	>14	5.6
27	05 20 04	-69 28 45	.031	.002	<0.0047	.012±.003	>6.6	2.6
29	05 20 25	-71 39 20	.023	.007	----	----	----	----
37	05 26 05	-69 15 51	.044	.011	<0.003	<0.01	>15	>4.4
38	05 26 24	-70 13 35	.025	.007	<0.0037	<0.013	>6.8	>1.9
40	05 27 59.5	-69 13 18	.033	.009	<0.003	<0.01	>11	>3.3
44	05 30 42.9	-66 56 35	.039	.006	<0.0026	<0.006	>15	>6.7
45	05 30 54	-70 48 25	.024	.005	----	----	----	----
46	05 32 18.4	-71 32 00	.035	.006	----	----	----	----
48	05 32 38	-66 33 16	.029	.006	<0.004	.0083±.0016	>7.3	3.5
56	05 35 13	-69 46 11	.036	.008	----	----	----	----
55	05 35 20	-69 22 01	.027	.008	----	----	----	----
58	05 35 39	-70 08 33	.034	.009	<0.0025	<0.0069	>13.5	>4.9
60	05 36 10.9	-67 36 17	.045	.009	<0.0027	0.008±.002	>16.5	5.6
63	05 37 23	-69 32 55	.042	.009	<0.003	<0.006	>14	>6.9
64	05 37 33.3	-70 10 27	.040	.010	<0.0026	<0.0066	>15	6.7
73	05 39 04.3	-69 11 08	.043	.003	<0.0018	<0.004	>24	>11
76	05 39 46	-69 49 23	.069	.014	<0.002	<0.005	>35	>14
81	05 42 25	-70 23 24	.031	.006	----	----	----	----
86	05 46 46	-68 35 15	.020	.006	----	----	----	----
96	05 55 09	-67 48 46	.027	.006	----	----	----	----

COMMENTS.—Source 8: Both SIT and image-tube spectra (1982 Feb, Nov and 1983 Nov) show radial velocity has a range of ~100 km s^{-1} with a probable period near 4 days. Mean velocity indicates LMC membership; large photometric variations (Hodge and Wright 1967) are generally not seen in galactic X-ray binaries, so this may argue against the identification with the X-ray source.

Source 9: This O8 star shows both H and He II λ4686 emission; the velocities show it to be a LMC member. The same comment about its apparent large photometric variations applies as for source No. 8. Pakull 1984 has found Sanduleak 70-36 to be an ellipsoidal variable with a period of 6.9 days and suggests it may be the optical counterpart. However, this star lies about 70″ SW of the current X-ray position and is outside the 90% confidence error box.

Source 37: *U*, *B*, *R* plates taken; finding chart given in this paper. Estimated magnitude of candidate star is ~16.4.

Source 56: *U*, *B*, *R* plates taken; finding chart given in this paper.

Source 55: SE component of double is a galactic ~K star; both stars of this pair are ~13 mag.

Source 58: The star 6″ south of V2690 shows velocity of ~180 km s^{-1} from SIT spectra (1982 Nov and 1983 Nov); more data are needed to confirm the identification.

Source 63: *U*, *B*, *R* plates taken; finding chart given in this paper. Star 1 (observed 1983 Nov) is a foreground A–F star. Several blue objects are marked.

Source 64: *U*, *B*, *R* plates taken; finding chart given in this paper.

Source 81: Star 1 is an early-A star in the LMC, but identification with the X-ray source is uncertain; *U*, *B*, *R* plates taken; finding chart given in this paper.

TABLE 2—*Continued*

Source	LMC Member?	Comments on X-ray data	Comments on Optical data	Footnotes
8	yes?	Variable	V 5542; m_B~15.6; O9 star; var RV; ~m 0.9; uncertain i.d.	*
9	yes		V 2289; O8e star: Δm~0.8; m_B~14.4;var. R.V.?	*
15	no?		G8 IV; v.wk. CaII em; possibly RS CVn?	
17		Candidate SNR	faint blue cluster here; star in cluster?	
27		Candidate SNR	candidate very blue star on Schmidt plates; needs confirmation	
29		Variable	only very faint stars in field, no candidates	
37	yes	Variable	v. wk. abs. lines; ~B0 ; in em. neb; var. wk. broad HeII (4686) em.	*
38			Blue star in field is LMC A star; not strong candidate	
40			several faint blue stars in field should be observed	
44			several faint blue stars in field should be observed	
45			no obvious candidates on Schmidt plates	
46			a carbon star at X-ray position seems an unlikely candidate	
48		Candidate SNR		
56			several candidate blue stars in field	*
55	yes?	Variable	~B2 star near center of field is north component of pair; weak neb. em.	*
58	yes?		late B star lies 6 arc seconds south of V2690; m_B~16.5	*
60		Candidate SNR	candidate blue star is S member of double close to X-ray position	
63		Variable	several faint, blue candidates	*
64		Variable	candidate faint blue star in field	*
73		Variable	too near 30 Dor to tell anything on survey plates	
76		Variable	blank field on survey plates	
81	yes?	Variable	early A star in LMC; i.d. uncertain	*
86			candidate very faint blue star on survey plates; more data needed	
96			candidate emission object and blue star in field; more data needed	

detailed consideration of the number of foreground and background interlopers expected. The result is a rather complete picture of the X-ray source populations of the LMC for luminosities $L_x > 3 \times 10^{35}$ ergs s^{-1}.

III. OPTICAL OBSERVATIONS

a) The Data

Nearly all of the optical work has been carried out at Cerro Tololo Inter-American Observatory, with a variety of instruments and techniques. In order initially to identify candidate objects, we obtained unwidened objective prism (spectral) plates using the UV transmitting thin prism on the Curtis Schmidt telescope. These spectra were taken on IIIa-J plates in good seeing for a large region around the LMC. The dispersion is about 1000 Å mm^{-1} at Hγ. Spectra of stars to about 18–19 mag are visible, but, because of the small plate scale (96″ mm^{-1}), overlapping images become a problem in crowded regions along the LMC Bar and in 30 Dor. Therefore, we also obtained slitless spectra using the blue grism at the prime focus of the 4 m telescope for 23 fields along the Bar and around some of the X-ray sources. Because of the much larger plate scale ($\sim$19″ mm^{-1}) superposition of images is less of a problem. These plates reach to about the same magnitude. For 12 fields, as noted in Tables 1 and 2, one of us (J. R. T.) has obtained plates in U, B, and R with the image-tube camera on the Yale 1 m telescope. These were examined for objects of peculiar color, especially UV-bright objects. These plates reach to $B \sim 20.5$. Finding charts for a number of sources derived from these plates are shown as Figures 2 and 3. Photometry done with the 0.9 m telescope for some of the objects is reported in Table 3.

For all of the X-ray positions, overlay plots were generated at the scale of the Hodge and Wright (1967) atlas of the LMC

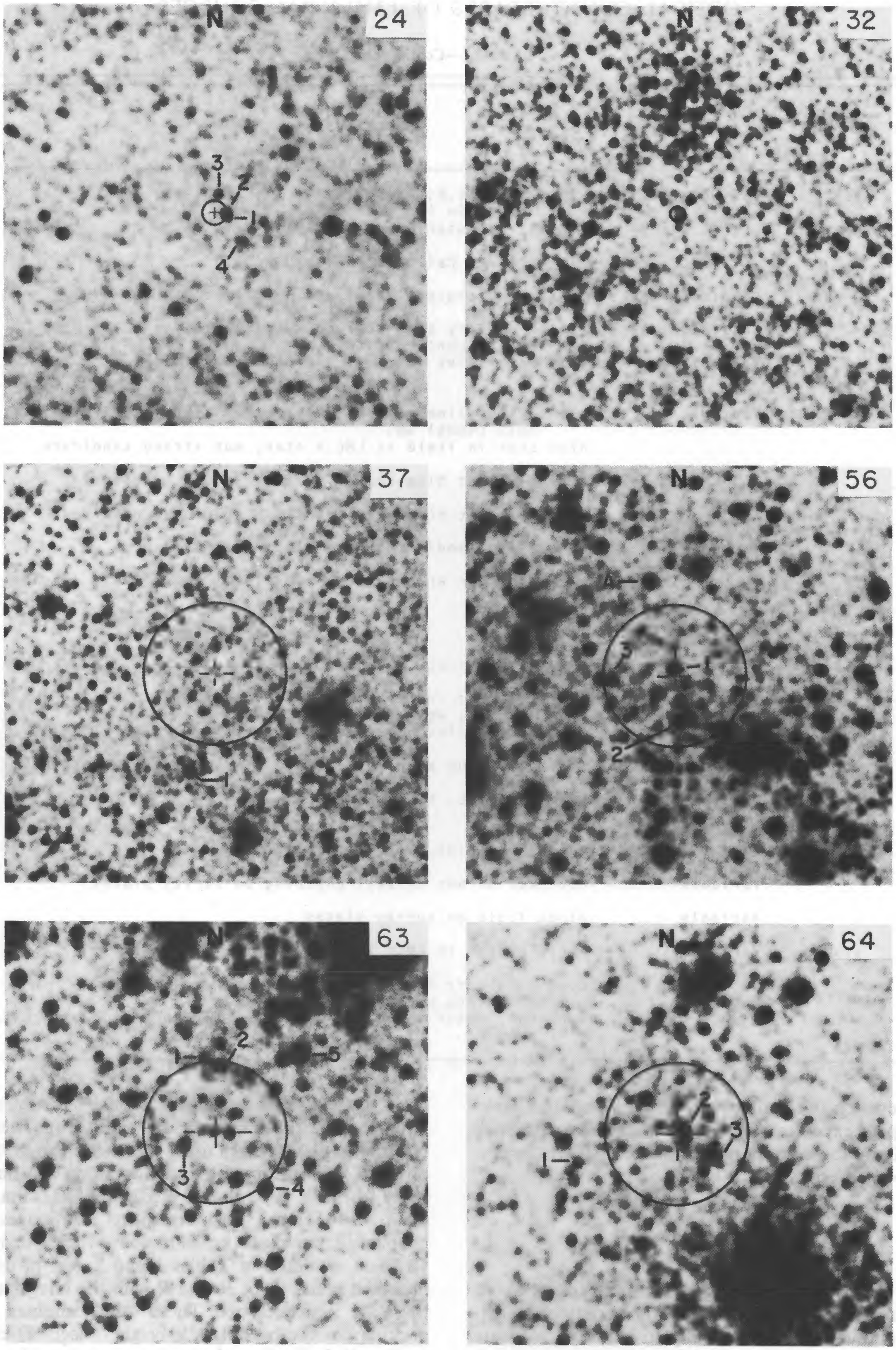

FIG. 2.—*B* band photographs of LMC fields from 1.0 m image-tube plates. X-ray error circles (90% confidence) and possible candidates are marked. The fields are 3 arcmin^2; north is at the top of each photograph. *Source 24* (HRI): star 1 is the dMe indicated in Table 1, and star 2 is the fainter UV-bright companion mentioned in the notes to Table 1. *Source 32* (HRI): the brightest object in the small error box is the Seyfert galaxy indicated in Table 1. *Source 37* (IPC): star 1 is the B star candidate described in Table 2. *Source 56* (IPC): stars 1, 2, and 3 are all blue. The faint star SW of no. 1 may be UV bright. *Source 63* (IPC): star 1 is an A star. Stars 2, 3, 4, and 5 have early-type spectra; 2 and 3 are very blue. *Source 64* (IPC): star 1 is UV bright; stars 2 and 3 have A type spectra.

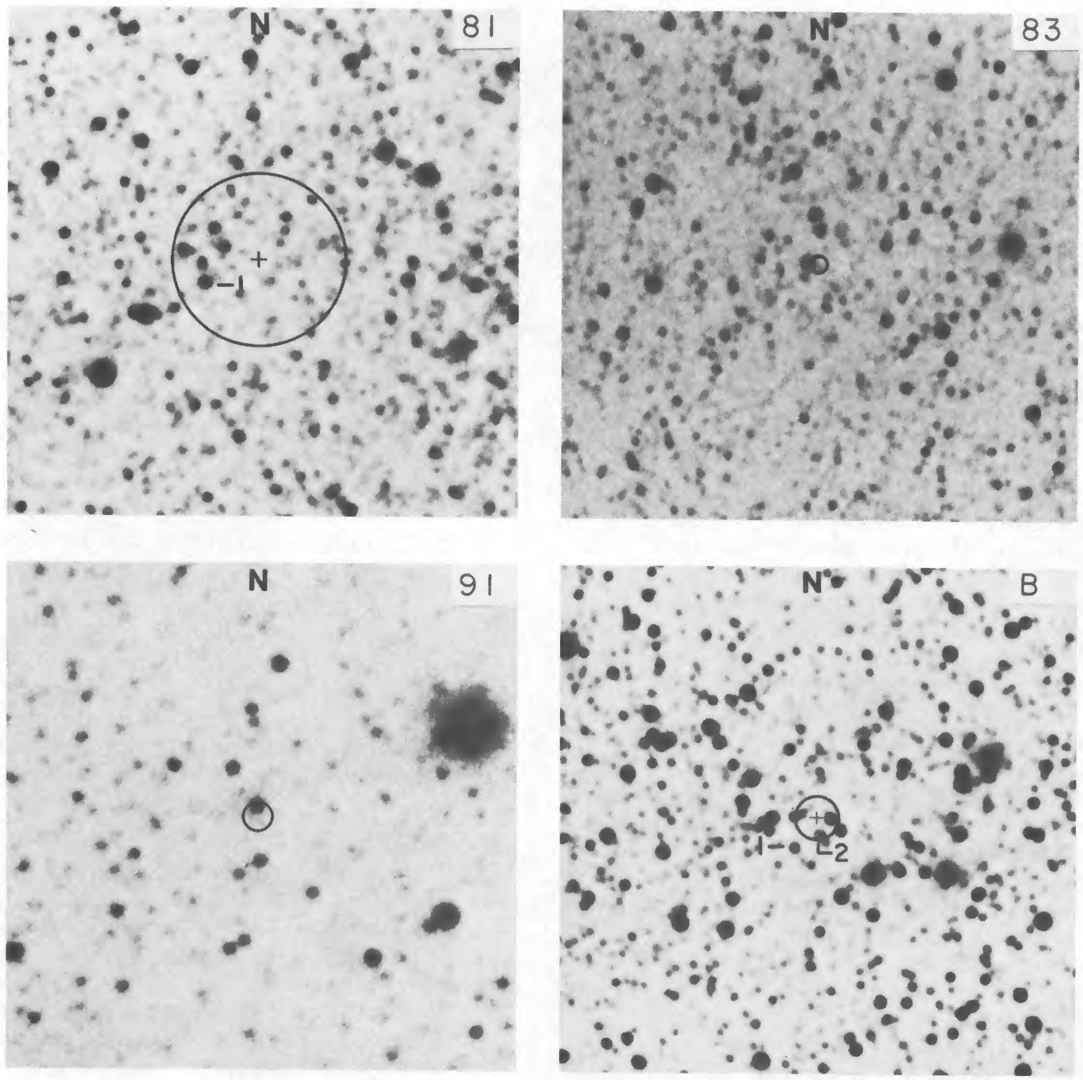

FIG. 3.—*B* band photographs of further LMC X-ray fields, as in Fig. 2. *Source 81* (IPC): object 1 is an LMC A star. *Source 83* (HRI): the candidate star is the object on the E edge of the small error box and is the brightest star in the error circle. This binary is described in Table 1 and its notes. The star appears to be a firm identification. Pakull (1983) has identified the same candidate star. *Source 91* (HRI): the error circle encloses the Seyfert galaxy described in Table 1. It is the brightest object within the error circle. *Source B* (HRI): star 1 is UV bright; star 2 has a late-type spectrum. The identification of this source with star 2 is not at all certain.

TABLE 3

LARGE MAGELLANIC CLOUD X-RAY SOURCE PHOTOMETRY

Source	V	$U-B$	$B-V$	$V-R$	Remarks
6..........	12.36	+1.00	+1.28	+0.92	Photometer icing problems;
	(1)	(3)	(2)	(1)	accuracy about ±0.1 mag
A..........	10.17	0.29	0.76	0.42	
	(0.5)	(1)	(1)	(1)	
18..........	13.42	1.14	1.56	1.22	
	(1.4)	(5)	(2)	(1.4)	
20..........	10.67	0.28	0.72	0.44	
28..........	10.99	0.28	0.76	0.47	
	(0.7)	(1.3)	(1.2)	(0.9)	
33..........	12.89	0.83	1.42	1.14	Average of 2 nights
	(2)	(3)	(2)	(2)	
43..........	9.60	0.08	0.64	0.36	1981 Dec 19.34
	9.68	0.11	0.64	0.36	1981 Dec 20.36
					counting statistics errors
					very small; ~1%
69..........	12.05	1.04	1.32	0.91	
	(1.1)	(1.8)	(1.5)	(1.3)	

NOTE.—All measurements are from the 0.91 m telescope and photometer at CTIO on nights of 1981 December 19, 20, and 21 UT. Numbers in parentheses below quoted magnitudes are counting statistics uncertainties. When these are less than 2%, systematic uncertainties in the extinction and transformation coefficients probably dominate the error estimates.

and of the Science Research Council (SRC) charts. All of the objects in a given error box were examined on the direct plates, the Schmidt plates, and the grism plates (when available for that field). Often, in the case of HRI positions, only one candidate star or object was consistent with the position; it could thus be observed immediately with the spectrograph at higher dispersion. In other cases, spectra of several candidates such as blue stars, emission objects (especially QSOs and Seyfert galaxies), and obvious foreground stars were observed at higher dispersion. When the candidates turned out to be interesting stars in the LMC, an attempt was made to obtain enough data to understand the nature of the X-ray system. Moderate-resolution spectra have been obtained with the CTIO 4 m Ritchey-Chrétien spectrograph using both the SIT vidicon and the image-tube Singer camera for most of the candidate objects and with the Anglo-Australian Telescope (AAT) 4 m telescope and IPCS for a few candidates. Detailed studies have been carried out for LMC X-1, LMC X-3, LMC X-4, CAL 83, and A0538 − 66 (see references below).

b) *The Identifications*

In Tables 1 and 2 we list all of the HRI and IPC point sources, respectively, and present what data we have on their optical identifications. Of the 24 HRI sources, 13 are now identified with foreground stars. All are in the spectral range F–M with half being very cool dMe stars. The $L_x/L_{\rm opt}$ ratio for these stars is consistent with what is known from other studies (e.g., Vaiana *et al.* 1981; Helfand and Caillault 1982; Topka *et al.* 1982; Margon, Chanan, and Downes 1982).

Also in the HRI sample we have found three active galaxies, as listed in Table 1. For two fields (sources E and 87) we have not yet made a definite identification, while for source CAL B the identification is only tentative.

The situation with regard to the identification of the X-ray sources with only IPC positions is very incomplete. These, in general, are somewhat weaker sources and are more closely confined to the LMC Bar. CAL 8, CAL 9, and CAL 37 may be associated with LMC binaries, but their identifications are not yet final. CAL 15 appears to be a foreground galactic star. Possible B or A type stellar candidates in the LMC are proposed for sources 55, 58, and 81. The position of CAL 8 is consistent with that of V5542 (Hodge and Wright 1967), which is a B3 star and appears to be a spectroscopic binary of period 4 days in the LMC, which we provisionally consider identified. Sources 9 and 37 are both OB stars with broad variable He II λ4686 emission and are very likely correctly identified as Population I LMC binaries. CAL 58 may be identified with the LMC B star which lies about 6″ south of V2690 (Hodge and Wright 1967). Its velocity (180 km s^{-1}) is not variable in our data but is low for the LMC, so that it may well be a binary. Many of the remaining sources lie in crowded fields, and while some have candidates chosen from objective prism or grism surveys (see Table 2), the follow-up, confirming spectroscopy has not been done.

In some fields we have been unable even to propose candidates, implying counterparts with absolute magnitudes fainter than $M_v \sim 0$, if they are in the LMC. At this point little more can be said about the IPC source identifications except that we would expect to find fewer and perhaps fainter foreground stars than in the HRI sample. Considering the more central location of the IPC sources in the LMC, we expect a sizable fraction of these to be LMC sources. From the lack of optically luminous candidates, we suggest that several may be Population II objects.

IV. DISCUSSION OF FOREGROUND AND BACKGROUND OBJECTS

As indicated above, our catalog of X-ray sources toward the LMC is contaminated by X-ray emitting stars in the Galaxy and by extragalactic objects (active galactic nuclei and galaxy clusters) beyond the LMC. In this section, we calculate the numbers of these interlopers expected in our survey region, comparing these predictions with the numbers of such objects already identified and constraining the number which remain among the unidentified portion of the sample.

a) *Background Interlopers*

The largest sample of identified extragalactic objects in the flux range of interest (0.01–1 IPC counts s^{-1}) reported to date is from the medium-sensitivity survey of serendipitous high galactic latitude sources (Gioia and Maccacaro 1983). Using the log N/log S relation derived from their completely identified sample of 86 extragalactic objects, we expect 2 ± 1, 9 ± 2, and 53 ± 10 background objects above flux thresholds of 0.1, 0.032, and 0.01 IPC counts s^{-1}, respectively, to appear in a 37 deg^2 region. In the present case, however, we are viewing these objects through the interstellar medium of the LMC. From the neutral hydrogen map of the Cloud (see Fig. 3 of LHG) we calculate that 35% of our survey region has a mean hydrogen column density $\langle N_{\rm H} \rangle \sim 2 \times 10^{20}$ cm^{-2}, while the remaining 65% has $\langle N_{\rm H} \rangle \sim 0.75 \times 10^{20}$ cm^{-2}. For an X-ray spectrum characterized by $kT \sim 1$ keV, these column densities will reduce the received flux in the IPC band by 20% and 5%, respectively. Thus, the corrected log N/log S predictions are 1.5 ± 1, 8 ± 2, and 44 ± 10 for the three flux thresholds. Note that these are the numbers to be expected in a complete survey over the 37 deg^2, and that in the lowest flux bin, our survey is only ~50% complete.

The extragalactic sources in the sample of Gioia and Maccacaro (1983) are ~75% active galactic nuclei (AGN) and 25% clusters. AGNs are, of course, point sources, have typical

IPC/HRI ratios of ~ 5 to ~ 15, and have expected optical magnitudes in the range $16 < m_V < 21$. Clusters, as a result of both their relatively hard X-ray spectra and the fact they are diffuse ($\sim 2'$–$10'$ diameters), will be undetectable in the HRI and will be very difficult to identify optically in the crowded star fields of the LMC. The AGNs may show variability on a time scale of months, but the majority are not expected to do so (Hailey, Helfand, and Ku 1980); the clusters will, of course, have constant flux. These results suggest that $\sim 2 \pm 1$ of the 9 remaining sources brighter than 0.032 counts s^{-1} which lack even provisional identifications are clusters of galaxies (sources 44 and 56 are possible candidates on the basis of their relatively hard IPC spectra); another ~ 2 of these sources, in addition to the objects reported in § III, should be AGNs ($f_x <$ 0.032 counts s^{-1}). We expect the majority of the faint IPC sources in LHG to be extragalactic. We do not discuss them further here, as their X-ray fluxes are below the cutoff for Table 4 objects.

b) *Foreground Interlopers*

While our expectations for the numbers of extragalactic interlopers are perfectly consistent with our identification results to date, the predicted numbers for foreground stars are somewhat less so. Gioia and Maccacaro (1983) found that $\sim 25\%$ of their serendipitous source population consisted of late-type stellar X-ray sources; in particular, they found six stars in their 90 deg^2 survey area above 0.032 IPC counts s^{-1}. In an optical magnitude-limited survey ($m_V < 10$) covering 240 deg^2, Helfand and Caillault (1982) found 50 stars later than A5 to be X-ray sources brighter than 0.01 IPC counts s^{-1}. These results suggest that the current survey area should include $\sim$ three and seven such stars above 0.032 and 0.01 counts s^{-1}, respectively. To date, we have 12 and 17 suggested stellar identifications above these thresholds.

Are some of these stellar counterparts likely to be misidentifications? Nearly all (>95%) serendipitous stellar sources brighter than 0.01 IPC counts s^{-1} have $m_V < 15$. All of the suggested foreground stellar identifications in our survey satisfy this criterion. Second, X-ray emitting late-type stars have X-ray to optical flux ratios in the range $10^{-6} < f_x/f_V <$ 10^{-1} (Vaiana *et al.* 1981); again, all of our identifications are consistent with this expectation. Finally, we can show that on statistical grounds, few of the identifications are likely to be spurious. At the galactic latitude of the LMC ($b \sim 35°$) the surface densities of stars brighter than $m_V = 12$ and $m_V = 15$ are ~ 42 and ~ 500 per deg^2, respectively (Allen 1973). Thus, for an HRI error box of ~ 75 arcsec^2 (6×10^{-6} deg^2), the *a priori* probabilities for finding a star this bright are ~ 2.5

TABLE 4

X-Ray Source Populations toward the Large Magellanic Cloud

Source Class	X-Ray Complete Sample (>0.032 counts s^{-1}) (52 sources)	X-Ray Flux-limited Sample (>0.02 counts s^{-1}) (65 sources)	Total Known Sources[a] (102 sources)
	Interlopers		
AGN:			
Identified	2	3	3
Candidates	0	0	0
Additional expected	(~3)	(~6)	(~12)
Clusters of galaxies:			
Identified	0	0	0
Candidates	0	0	0
Additional expected	(~2)	(~3)	(~7)
Stars:			
Identified	10	10	12
Candidates	1	1	2
Additional expected	(~0)	(~0)	(~1)
Unidentified	~5	~9	(~20)[b]
	LMC Members		
SNR:			
Identified	18	19	26
Candidates	3	5	5
Pop. I binaries:			
Identified	4	4	4
Candidates	3	6	7
Pop. II binaries:			
Identified	2	2	2
Candidates	0	0	0
Unidentified	~2	~2	(~15)[b]

[a] LHG survey plus new HRI sources reported here.

[b] This estimated is very sensitive to the assumption of $\sim 50\%$ completeness for the survey below 0.03 counts s^{-1}; it should be viewed as consistent with a ratio of ~ 25 interlopers to ~ 10 LMC members.

$\times 10^{-4}$ and $\sim 3 \times 10^{-3}$, respectively. Thus, even in the 24 HRI error boxes searched, the chance of a spurious identification is small. For the four weaker sources (4, 5, 85, and 92) identified by LHG with bright stars on the basis of IPC positions, where ~ 100 error boxes of $\sim 10^{-4}$ deg^2 each were examined, it is possible that one or two are misidentifications. (Note that these are below the 0.02 counts s^{-1} cutoff for objects in Tables 1 and 2.) The limiting optical magnitude of our search program ($m_V \sim 19$) virtually eliminates the possibility that any additional foreground stars will turn up amongst the unidentified sources in the complete ($f_x > 0.032$ counts s^{-1}) portion of our survey. For the fainter sources, at most three stars remain unidentified.

In summary, then, we have identified a total of 12–14 interlopers among the 52 sources in the complete flux-limited sample and expect no more than five additional ones among the remaining unidentified sources. For the fainter 48 sources in LHG, although only six interlopers have been tentatively identified, we expect that at least another 20 such sources, principally extragalactic objects, remain.

V. THE X-RAY SOURCE POPULATION OF THE LMC

In Table 4, we summarize all of the preceding results by source class for each of three samples of LMC X-ray sources: the complete flux-limited sample with $f_x > 0.032$ IPC counts s^{-1}; the incomplete but X-ray flux-limited sample of 65 sources with $f_x > 0.02$ IPC counts s^{-1} studied optically here; and the total sample of all known X-ray objects detected in the direction of the Cloud. We have discussed the interlopers in some detail above, and the population of LMC SNRs has been dealt with elsewhere (Mathewson *et al.* 1983). Here we review our results on the point source X-ray emitters that are LMC members.

Nine LMC X-ray binaries have been definitely or probably identified from our sample. Five of these were previously known LMC sources, and we have suggested four more candidates (CAL 8, CAL 9, CAL 37, and CAL 83) as Cloud members. A few additional sources (e.g., CAL 55, CAL 58, CAL 81, and CAL E) will probably ultimately be identified as LMC objects. This number is not unexpected if one makes a comparison with the stellar sources known in the Galaxy. The ratio of masses of the LMC and the Galaxy is about 1:10. There are about 100 stellar sources known in the Galaxy to the limiting X-ray luminosity surveyed in the LMC ($\sim 10^{35}$ ergs s^{-1}). Thus one might expect about 10 LMC sources if other differences in the two galaxies did not influence the X-ray source population.

In the Galaxy we have identified optically about 20 sources as massive, early-type X-ray binaries (both hot supergiants and Be star primaries), although because of obscuration in the galactic plane there must be at least twice as many such systems in the Milky Way than have been identified thus far. Another way of estimating the total number of massive binaries in the Galaxy is to consider that within 2.5 kpc of the Sun there are seven such Population I binaries complete to an X-ray luminosity of 10^{35} ergs s^{-1}. Thus, scaling up to the total disk area covered by spiral arms, one expects about 50 such Population I massive binaries in the Galaxy, in agreement with the number estimated above. In the LMC there appear to be at least four (and perhaps seven) such systems: LMC X-1, LMC X-3, LMC X-4, A0538−66 (CAL G) (and CAL 8, CAL 9, and CAL 37). At least one (LMC X-3), and possibly two (LMC X-1), of these systems probably contains a black hole (Cowley *et al.* 1983; Hutchings, Crampton, and Cowley 1983). LMC X-4 has a supergiant and a neutron star in a close binary system (e.g., Hutchings, Crampton, and Cowley 1978; Li, Rappaport, and Epstein 1978; Kelley *et al.* 1983) of the type quite common in the Galaxy. CAL G (A0538−66) and CAL 9 and CAL 37 are more closely related to the Be star systems in the Galaxy. CAL G has high and low states both optically and in X-rays. It also undergoes strong variations in both the luminosity and spectrum which appear to be related to a 16.7 day (orbital?) period (Johnston *et al.* 1979; Charles *et al.* 1983; Howarth *et al.* 1984; Pakull and Parmar 1981).

The total number of Population I sources is then at least four, probably seven, and may be $\gtrsim 10$, if the additional suggested candidates are confirmed. Again, this number is consistent with the number of such sources in the Galaxy, scaled down to the mass of the LMC.

Two other identified stellar sources in the LMC (LMC X-2 and CAL 83) show spectra which are characterized by a blue continuum and variable He II λ4686 emission rather like the Sco X-1 type sources in the Galaxy (McClintock, Canizares, and Backman 1978). Both of these LMC sources show variable radial velocity, but as yet we do not know their orbital periods and thus have no estimate of their masses. The optical emission appears to arise from a bright accretion disk in these systems, and one apparently does not see either of the underlying stars. In the Galaxy ~ 32 of these bulge sources are optically identified (Bradt and McClintock 1983), although again this number would increase by about a factor of 2 if there were not strong interstellar absorption in the direction of the galactic center, where many of these sources lie (see McClintock and Rappaport 1983). We know of five Population II objects (to the X-ray flux limit of the LMC survey) within 2.5 kpc of the Sun. Scaling this up by about a factor of 15, we expect ~ 75 Population II binaries in the halo of the Galaxy. Again this agrees well with our above rough estimate of twice the optically identified number. In the LMC, our optical search is substantially incomplete for these fainter objects. However, the two identified members of the class plus a few remaining members in our complete X-ray sample (see second column, last line of Table 4) again yield a number in substantial agreement with a simple scaling by galaxy mass from the Milky Way.

While the numbers of X-ray binaries in the LMC are as expected from a simple extrapolation from the Galaxy, the massive LMC sources do appear to be more X-ray luminous than their counterparts in the Galaxy (e.g., Clark *et al.* 1978). In Figure 4 we plot a histogram of $L_x/L_{\rm opt}$ for the LMC and the Milky Way high-mass systems. There are not enough of the fainter bulge (or Population II) type sources in the LMC to make a meaningful comparison. It may be significant that at least one, and possibly two, of the five high-mass sources in the LMC may contain black hole companions, while in the Galaxy only Cyg X-1 (and possibily SS 433 and Cir X-1) of the 20 well-studied, high-mass systems shows evidence for a black hole.

In the LMC, none of the X-ray sources occur in a globular cluster, whereas 13 galactic globular clusters contain X-ray sources brighter than 10^{33} ergs s^{-1} (Bradt and McClintock 1983; Hertz and Grindlay 1983). The Galaxy contains about 100 globular clusters, while there are only about a dozen old globular clusters in the LMC (Hartwick and Cowley 1982). Given that only $\sim 10\%$ of the clusters in the Galaxy contain strong X-ray sources, it is not surprising to find that none of the LMC clusters have been detected as X-ray sources. Furthermore, at least two of the outlying LMC clusters (NGC

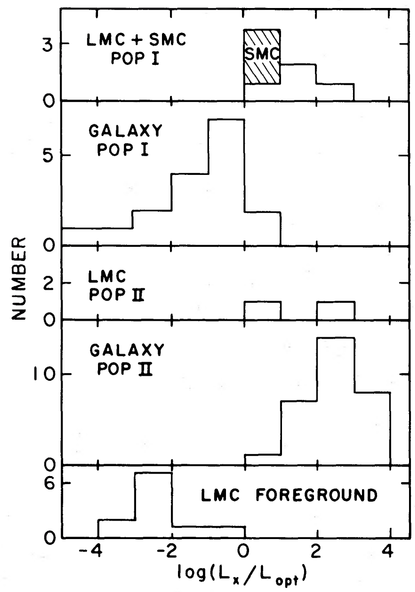

FIG. 4.—Histograms of L_x/L_{opt} for the LMC sources from this paper as compared with X-ray sources in the Galaxy (Bradt and McClintock 1983). Note the high values for the LMC Population I sources.

1841 and NGC 1466) were not even included in the *Einstein* LMC survey.

The spatial distribution of the identified LMC X-ray sources is shown in Figure 1. These few objects show no concentration toward the Bar or other star-rich fields. This distribution is quite unlike the strong concentration in the galactic plane shown by the massive X-ray binaries in the Galaxy. We note that the Galactic Population I sources have an rms z distance of $\sim$90 pc, which suggests they have high motions, but the mean distance of the massive binaries in the LMC from the star-rich fields is even greater. The still unidentified IPC sources do show a greater concentration toward the main body of the LMC, and, as noted above, we expect some of these will ultimately be identified with LMC members.

VI. SUMMARY

We have presented an extensive collection of new X-ray and optical data on the X-ray sources detected in the direction of the LMC. A total of 44 of the 65 sources brighter than 0.02 IPC counts s^{-1} ($\sim 5 \times 10^{-13}$ ergs cm^{-2} s^{-1}) have now been identified, and another 10 have suggested optical counterparts. Twenty-eight of the certain identifications are LMC members, including 19 SNRs. There are nine X-ray binaries or probable binaries. Of the remaining 16 sources, we expect a roughly equal division between extragalactic interlopers and LMC members, predominantly Population II binaries and SNRs.

The total number of stellar X-ray systems per unit mass is similar in the LMC and in the Galaxy. The mean X-ray luminosity of the LMC stellar systems appears to be higher than that in the Galaxy, which could be related to the lower metal abundance in the LMC, as has been discussed by previous authors (e.g., Clark *et al.* 1978). The optical luminosities of the identified LMC X-ray systems are similar to their counterparts in the Milky Way.

The distribution of massive X-ray systems is not concentrated in the optically luminous regions of the LMC, as might have been expected by comparison with the concentration in the disk of similar systems in the Galaxy. There is some evidence, based on admittedly small numbers, that a higher percentage of collapsed companions may be black holes rather than neutron stars in the LMC. At present nothing is known about the masses of the two Sco X-1 type systems in the LMC, so that comparison with similar Galactic systems is not yet possible.

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P. A. CHARLES: Department of Physics, University of Oxford, South Parks Rd., Oxford, OK1 3RQ, England, UK

A. P. COWLEY: Department of Physics, Arizona State University, Tempe, AZ 85287

D. CRAMPTON and J. B. HUTCHINGS: Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, 5071 West Saanich Road, Victoria, B.C. V8X 4M6 Canada

T. T. HAMILTON and D. J. HELFAND: Columbia Astrophysics Laboratory, Columbia University, 538 W. 120th St., New York, NY 10027

J. R. THORSTENSEN: Department of Physics and Astronomy, Dartmouth College, Wilder Hall, Hanover, NH 03755