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LOCATION OF THE RECURRENT (LMC?) X-RAY TRANSIENT A0538−66 WITH THE *HEAO 1* SCANNING MODULATION COLLIMATOR

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ABSTRACT

Two brief ($\sim 12^h$) X-ray flares from the direction of the Large Magellanic Cloud have been observed with the *HEAO 1* scanning modulation collimator. It is argued that both originated from the recurrent fast transient A0538−66, first observed with the *Ariel 5* satellite. A precise position for the source is obtained, and a B2 Iab star in the Large Magellanic Cloud is suggested as the optical counterpart. Evidence for a $16^d.66$ periodicity in the outburst times is presented and discussed.

Subject headings: X-rays: sources

I. INTRODUCTION

The transient X-ray source A0538−66 was discovered with the *Ariel 5* satellite during an extended observation of the Large Magellanic Cloud (LMC) in 1977 June and July (White and Carpenter 1978). Two brief ($\sim 12^h$) outbursts were observed, separated by $\sim 17^d$, during which the source reached a peak intensity ~10–20% of the Crab. The spectrum during the first outburst was well described by an optically thin thermal bremsstrahlung model with $kT = 6.5$ keV and no detectable low-energy cutoff ($N_H < 2 \times 10^{22}$ cm^{-2}; White and Carpenter 1978).

We report here the detection of two further transient outbursts from the direction of the LMC, observed with the *HEAO 1* modulation collimator in 1977 October and November. We conclude that all four events probably originated from the same source, A0538−66, for which a precise position has been determined and a possible counterpart suggested. The outburst times for the four events suggest a $16^d.66$ interval, or multiple thereof, between successive flares.

II. OBSERVATIONS AND RESULTS

The observations were made with the scanning modulation collimator on *HEAO 1* (Gurksy *et al.* 1978) between 1977 August 17 and December 25. The instrument consists of two four-grid modulation collimators of FWHM 30″ (MC1) and 120″ (MC2), respectively. Data taken when the instrument's field of view included the LMC (every $\sim 30^m$ except during Earth occultation or passage through the South Atlantic Anomaly) were binned as described by Gursky *et al.* (1978); the data were subsequently searched for evidence of unusual behavior on an orbit-by-orbit basis.

On two occasions, evidence was found for the presence of a source other than LMC X-1, X-2, X-3, or X-4. Lines of position determined from the MC1 and MC2 data yield a large number of possible intersections within which the source may be located. Data from the *HEAO 1* Large Area Sky Survey (LASS), furnished by the NRL group, confirm the existence of the source and provide lines of position which greatly reduce the number of possible MC intersections.

The first outburst was observed in data taken 1977 October 7 at ~1200 UT. In a four orbit superposition, 9 σ detections were obtained in both collimators. The source was too weak for a light curve to be obtained with the modulation collimator. Data taken when LMC X-1 was in the coarse collimator (4° × 4° FWHM) field of view were excluded so as not to bias the position measurement.

The LASS lines of position and the MC intersections for this detection are shown in Figure 1*a*. The MC lines of position exclude LMC X-4 as the source of the outburst. In addition, LMC X-4 was in eclipse (Li, Rappaport, and Epstein 1978) during part of the time when the source was visible in the LASS data. The center of the A0538−66 error region was $\sim 1^\circ.9$ from the *HEAO 1* scan circle during the four-orbit sum, implying an average flux density of 37 ± 7 μJy for a source in this region (for a Crab-like spectrum averaged over 1.5–13.5 keV; 1 μJy ≡ 0.242×10^{-11} ergs cm^{-2} s^{-1} keV^{-1}).

The second outburst occurred 1977 November 9 at ~1700 UT. A six-orbit sum yields 8 σ and 5 σ detections in MC1 and MC2, respectively, corresponding to a flux density of 18 ± 4 μJy for a source located near the A0538−66 error box ($\sim 1^\circ.1$ from the scan circle). The LASS line of position for this event intersects that of the October 7 event within the A0538−66 error box (Fig. 1*b*). As before, the MC lines of position rule out LMC X-4 as the source of the flare (although it was not in eclipse during this event). The LASS lines of position

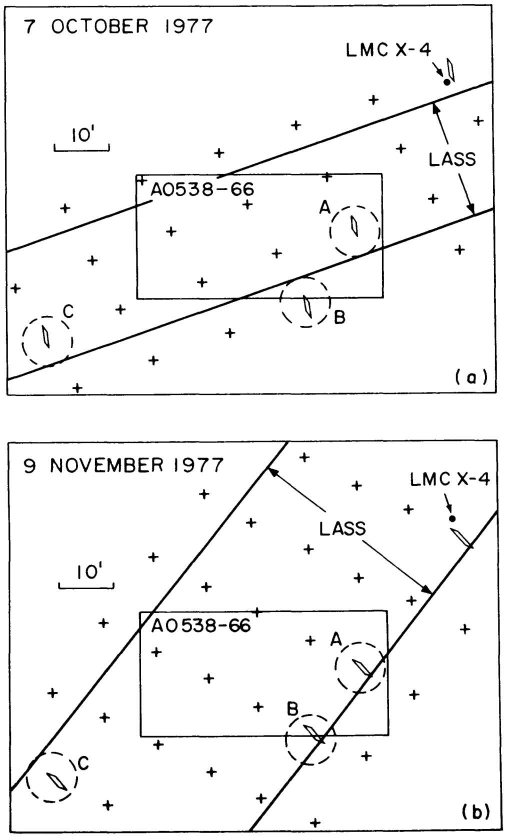

FIG. 1.—Positions for A0538−66: MC intersections and LASS LOP for the two *HEAO 1* observations of A0538−66. Only a few of the MC (90% confidence) intersections are shown; the centers of others are indicated by crosses. The MC LOP exclude LMC X-4 as the source of the outbursts. Positions consistent with all four sets of MC LOP are contained in the circled areas A, B, and C. The center of the *Ariel 5* error region is $\alpha(1950.0) = 5^{\rm h}38^{\rm m}8$, $\delta = -66°54'$ (White and Carpenter 1978).

for each event exclude the other known sources in the LMC (including H0544−665; Johnston *et al.* 1979; Johnston 1978).

The temporal behavior of the source and the positional coincidence of the LASS lines of position (LOP) with the A0538−66 error region strongly suggest that both outbursts came from this source. Further evidence that this is the case follows from a consideration of the onset times of the four outbursts (Table 1). The interval between the two events observed with *Ariel 5* (events I and II) is $16^{\rm d}81$, with an uncertainty of $\pm 0^{\rm d}07$. The interval between the two observed with *HEAO 1* (events III and IV) is $33^{\rm d}24 \pm 0^{\rm d}08$, almost exactly twice ($1.98 \pm 0.01$) the previous interval. The time between events II and III is $83^{\rm d}28 \pm 0^{\rm d}07$, nearly 5 times ($4.95 \pm 0.02$) the interval between I and II. This suggests the presence of a "window" every $\sim 17^{\rm d}$ within which a flare may occasionally occur. The data cannot, of course, exclude a fundamental period which is a submultiple of this interval.

TABLE 1

OUTBURST TIMES FOR A0538−66

Event	Date (1977)	Onset of Flare (JD−2443000)	Uncertainty (days)	Reference
I........	June 29	323.88	±0.04	(1)
II.......	July 16	340.69	0.03	(1)
III......	Oct. 7	423.97	0.04	(2)
IV......	Nov. 9	457.21	0.04	(2)

REFERENCES.—(1) White and Carpenter 1978. (2) Present work.

A least-squares fit to the onset times yields:

$$T_0 = (2443323.96 \pm 0.03) + (16.662 \pm 0.006)n\ , \quad (1)$$

where T_0 is the predicted time of the outburst. The observed events correspond to $n = 0$, 1, 6, and 8. All four outbursts begin within 2 hours of the times given by equation (1). It is thus highly probable that all four events originate from A0538−66, and that this source exhibits a $16^{\rm d}66$ periodicity in the timing of its outbursts. We note, however, that the timing data of Table 1 are apparently inconsistent with an exact periodicity: the deviation from equation (1) is as great as 2 hours (0.5% of the period), about twice the uncertainty in the onset time.

The MC1 data were summed into 10-orbit sets and searched for evidence of other outbursts from this source. No source detections at a significance level of $4\,\sigma$ or greater were found which could not be attributed to one of the other known LMC sources. The approximate $4\,\sigma$ upper limit on the 10-orbit average flux density of the source varies from $\sim 27\ \mu$Jy at $n = 3$ to $\sim 9\ \mu$Jy near $n = 10$ (Fig. 2), at which time LMC X-3

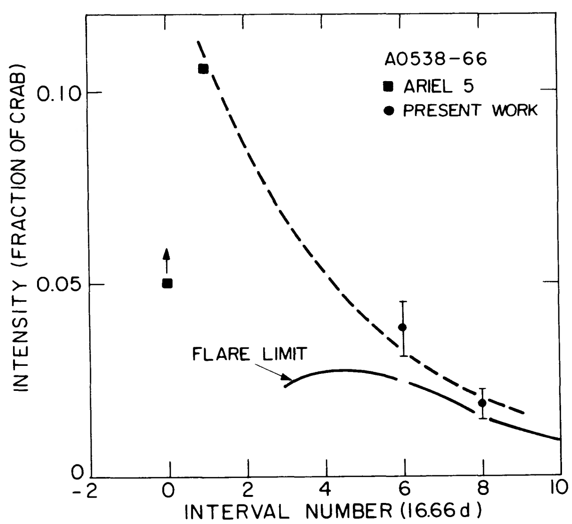

FIG. 2.—Long-term light curve of A0538−66: $\sim 8^{\rm h}$ average intensities from *Ariel 5* (*squares*, White and Carpenter 1978) and *HEAO 1* (*circles*, present work). The solid curve indicates approximate $4\,\sigma$ upper limits on the $15^{\rm h}$ average intensity of the source. The dashed curve illustrates the approximately exponential decay (time constant ~ 2 months) of the flare intensities. The overall average intensity from $n = 3$ to $n = 10$ is less than 0.001 Crab ($4\,\sigma$ upper limit), a factor of ~ 200 below the peak intensity observed with *Ariel 5*.

became too bright for an effective search to be made. About 15% of the data before this time could not be used to determine upper limits due to source confusion, pointing maneuvers, or the unavailability of data. We have carried out a cross-correlation analysis on the entire data set (Johnston *et al.* 1979) and place a 4 σ upper limit of 0.9 μJy (1.5–13.5 keV) on the time-averaged flux density of any persistent source in the vicinity of the A0538−66 error region.

The overlap of all four sets of MC lines of position gives a set of possible locations for the transient (Table 2). Only three intersections are consistent with both LASS lines of position (circles A, B, and C in Figs. 1*a*,*b*; Fig. 3 [Pl. L2]). Two of these regions are unlikely locations for the source: one (C) falls well outside the *Ariel 5* error region, while another (B) shows only a slight overlap of the 90% confidence lines of position. The preferred intersection (A) is consistent with both LASS lines of position and with the *Ariel 5* error region. This region is located in the direction of the stellar aggregate NGC 2034, part of the association LH 84 (Lucke and Hodge 1970). Selected stars in the vicinity have been studied photometrically by Dachs (1972), who classified the brightest star in the overlap of all four sets of LOP (star 19 in Fig. 3) as a probable LMC member with a spectral type of B2 Iab. His photometric observations yielded $V = 12.80$, $B - V = -0.13$, $U - B = -0.88$, with a color excess of $E_{(B-V)} = 0.02$ mag. We measure its position to be:

$$\alpha(1950.0){:}\ 5^{\rm h}35^{\rm m}46\overset{\rm s}{.}4, \qquad \delta{:}\ -66°52'10'',$$

with an uncertainty of ∼3″. We are aware of no other observations of this star. On the basis of its early spectral type and its location within the *HEAO 1* error region, this star is suggested as a promising candidate for the optical counterpart.

TABLE 2

POSITIONS FOR A0538−66

Event III (1977 October 7)		
Centers of MC1 and MC2 intersections (Fig. 1*a*):		
Region A:	$5^{\rm h}35^{\rm m}42\overset{\rm s}{.}5$,	$-66°52'40''$
	$83\overset{\circ}{.}9271$,	$-66\overset{\circ}{.}8779$
Region B:	$5^{\rm h}37^{\rm m}16\overset{\rm s}{.}2$,	$-67°07'44''$
	$84\overset{\circ}{.}3174$,	$-67\overset{\circ}{.}1289$
Region C:	$5^{\rm h}45^{\rm m}50\overset{\rm s}{.}1$,	$-67°12'58''$
	$86\overset{\circ}{.}4590$,	$-67\overset{\circ}{.}2162$
Error regions (offsets in seconds of arc from above positions):		
151″N, 61″N, 151″S, 61″S		
43 E, 8 W, 43 W, 8 E		
Event IV (1977 November 9)		
Centers of MC1 and MC2 intersections (Fig. 1*b*):		
Region A:	$5^{\rm h}35^{\rm m}39\overset{\rm s}{.}8$,	$-66°53'11''$
	$83\overset{\circ}{.}9159$,	$-66\overset{\circ}{.}8866$
Region B:	$5^{\rm h}37^{\rm m}16\overset{\rm s}{.}6$,	$-67°05'40''$
	$84\overset{\circ}{.}3190$,	$-67\overset{\circ}{.}0945$
Region C:	$5^{\rm h}45^{\rm m}41\overset{\rm s}{.}8$,	$-67°14'14''$
	$86\overset{\circ}{.}4243$,	$-67\overset{\circ}{.}2372$
Error regions (offsets in seconds of arc from above positions)		
118″N, 112″N, 118″S, 112″S		
133 E, 45 E, 133 W, 45 W		

III. DISCUSSION

The existence of a class of brief ($\lesssim$1 week) high-galactic-latitude transients is now well established (Rappaport *et al.* 1976; Cooke 1976; Ricketts, Cooke, and Pye 1978; Schrijver *et al.* 1978; Griffiths *et al.* 1979). These sources exhibit a wide variety of spectral and temporal behaviors, and their nature remains largely a mystery. Few have been positioned with high precision, and none have been convincingly identified with optical objects.

The association of A0538−66 with an extragalactic object behind the LMC may probably be discounted due to the absence of non-stellar objects in the error regions, and to the high luminosities involved: at a distance of d Mpc, the maximum 2–17 keV luminosity of the second flare observed with *Ariel 5* (peak intensity ∼20% of the Crab; White and Carpenter 1978) would be $L_{\rm max} = d^2\ 2.8 \times 10^{41}$ ergs s^{-1}.

The frequency of occurrence of fast transients is not known well enough to allow a statistical estimate of whether A0538−66 is a probable LMC member or, instead, a relatively nearby galactic object. In the latter case the source may be at a distance of 0.1-1 kpc, implying a peak luminosity of $10^{(34.5\pm1)}$ ergs s^{-1}. The absence of stars with $m_B \lesssim 13$ ($M_B \lesssim 3$ for $d = 1$ kpc) near the error regions rules out a galactic supergiant, giant, or main-sequence star earlier then spectral type ∼F (Allen 1973) as the possible counterpart. As discussed by Rappaport *et al.* (1976), a plausible model for this type of source may involve a white dwarf and a low-luminosity dM or dK star. The latter are numerous in the solar neighborhood, and may be responsible for mass transfer if located in close binary systems. A luminosity of 10^{34} ergs s^{-1} is in accord with the calculations of Katz (1977; see also Kylafis and Lamb 1978; Fabian, Pringle, and Rees 1976) for accretion onto a white dwarf, although the spectrum of A0538−66 is considerably softer than predicted by this model ($kT \approx 30$–100 keV) and does not exhibit the expected low-energy cutoff.

On the other hand, A0538−66 may well be a member of the LMC, and thus at a distance of ∼46 kpc (de Vaucouleurs 1978). The peak luminosity is high (∼6×10^{38} ergs s^{-1}; White and Carpenter 1978), but brief (∼$20^{\rm m}$ duration) outbursts of this intensity have been observed on a number of occasions from LMC X-4 (Epstein *et al.* 1977; White 1978).

The envelope of the long-term curve of A0538−66 (Fig. 2) is similar to the light curves of a number of longer-duration galactic transients (Kaluzienski 1977). The apparent periodicity of the outbursts suggests a binary nature with the flares occurring near some particular point in the orbit. One model with this feature is the eccentric binary hypothesis, discussed by a number of authors (e.g., McCluskey and Kondo 1971; Avni, Fabian, and Pringle 1976; Cominsky *et al.* 1978*a*) in connection with longer-duration galactic transients (e.g., Cominsky *et al.* 1978*b*). In a binary system with a wide orbit, the

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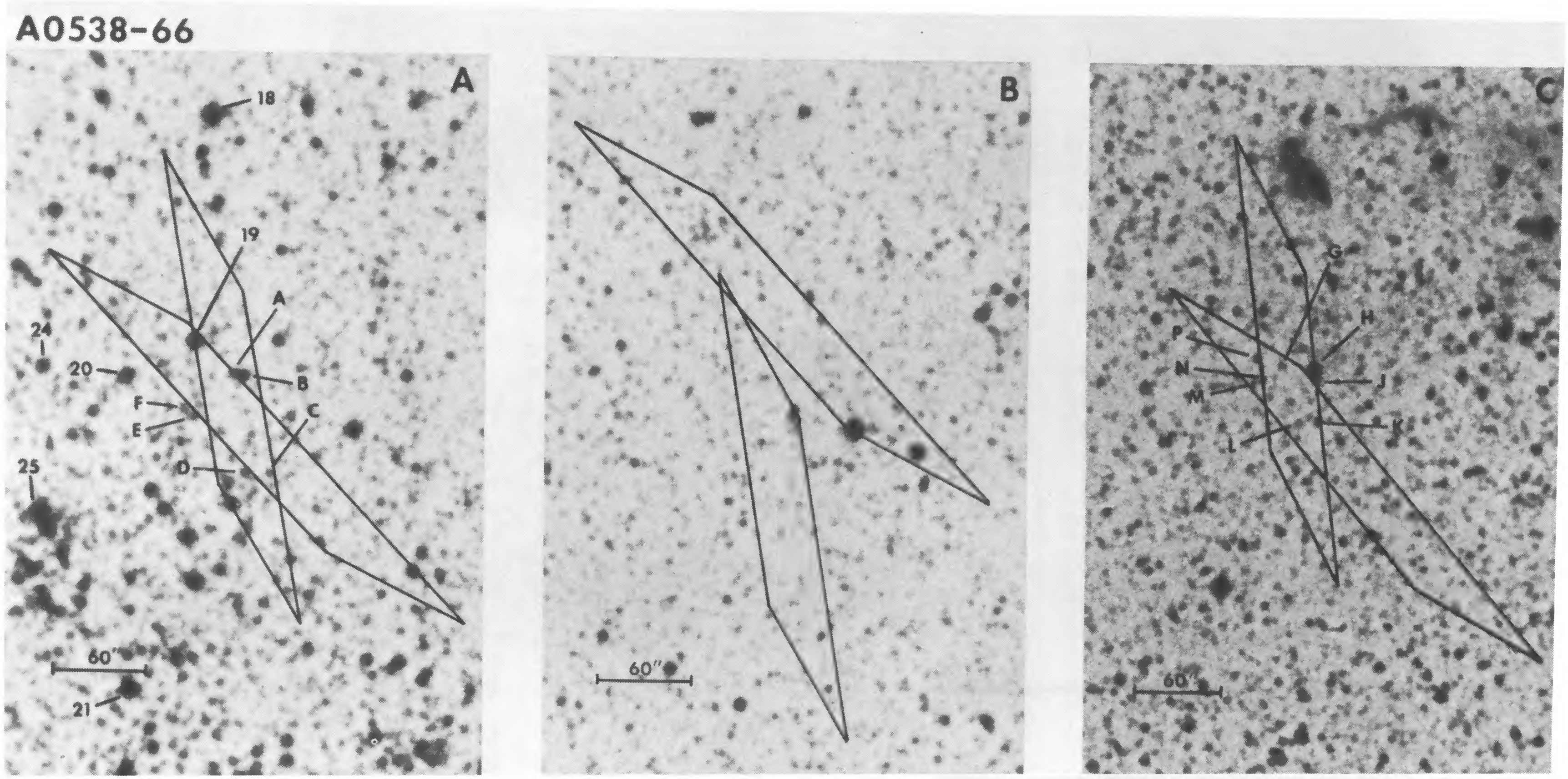

FIG. 3.—Finding charts for A0538−66 prepared from the ESO (B) Sky Survey negatives. Each of the two *HEAO 1* observations of A0538−66 yields a set of error regions (parallelograms) which are the intersections of the MC1 and MC2 90% confidence lines of position. The intersections of the parallelograms from the two observations gives a set of possible source locations. Three of these (see Fig. 1) are consistent with the LASS lines of position; only two (A and B) are also consistent with the *Ariel 5* error region (White and Caprenter 1978). Star numbers are from Dachs (1972); star "19" is the suggested counterpart of A0538−66.

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accretion rate due to the stellar wind of the primary may be very low until the primary goes through a period of enhanced mass loss (cf. 4U 0115+63: Cominsky *et al.* 1978*a;* Johnston *et al.* 1978; Rappaport *et al.* 1978). For an orbital eccentricity e, the ratio of maximum to minimum luminosity is given by $[(1 + e)/(1 - e)]^2$ (Avni, Fabian, and Pringle 1976). If the optical counterpart of A0538−66 is the B2 Iab star suggested above (mass $\sim 20\, M_\odot$, radius $\sim 30\, R_\odot$), and if we assume that the mass of the compact secondary is $\sim 1\, M_\odot$ and that the flare interval ($16^d.7$) is the orbital period, then we can place an upper limit of ~ 0.4 on the orbital eccentricity of the system. Thus, for spherically-symmetric mass loss from the primary, the orbital eccentricity is apparently insufficient to explain the intensity modulation observed.

An alternative binary model may involve a rapidly rotating Be star undergoing mass loss primarily from its equatorial region. Systems of this type have been associated with both persistent and transient Galactic sources (Chevalier and Ilovaisky 1975; Stier and Liller 1976; Maraschi, Treves, and van den Heuvel 1976; Bradt *et al.* 1977). If the orbital plane of the system is inclined to the equatorial plane of the Be star, this material would be encountered twice per orbit by the compact secondary. The absence of detectable flux during some encounters may be due to spatial inhomogeneities in the accreting material.

This model may be applicable to some of the other fast transients, where the absence of reported periodicities may be due to long binary periods or to infrequent episodes of enhanced mass loss by the primary. Optical observations of the A0538−66 system may be able to establish the presence of a binary system, and lead to a determination of the optical mass function.

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REFERENCES

Allen, C. W. 1973, *Astrophysical Quantities* (3d ed.; London: Athlone Press).
Avni, Y., Fabian, A. C., and Pringle, J. E. 1976, *M.N.R.A.S.*, **175**, 297.
Bradt, H. V., *et al.* 1977, *Nature*, **269**, 21.
Chevalier, C., and Ilovaisky, S. 1975, *IAU Circ.*, No. 2778.
Cominsky, L., Clark, G. W., Li, F., Mayer, W., and Rappaport, S. 1978*a*, *Nature*, **273**, 367.
Cominsky, L., Jones, C., Forman, W., and Tananbaum, H. 1978*b*, *Ap. J.*, **224**, 46.
Cooke, B. A. 1976, *Nature*, **261**, 564.
Dachs, J. 1972, *Astr. Ap.*, **18**, 271.
de Vaucouleurs, G. 1978, *Ap. J.*, **223**, 730.
Epstein, A. Delvaille, J. P., Helmken, H., Murray, S., Schnopper, H., Doxsey, R., and Primini, F. 1977, *Ap. J.*, **216**, 103.
Fabian, A. C., Pringle, J. E., and Rees, M. J. 1976, *M.N.R.A.S.*, **175**, 43.
Griffiths, R. E., *et al.* 1979, in *X-Ray Astronomy*, ed. L. E. Peterson and W. Baity (in press).
Gursky, H., *et al.* 1978, *Ap. J.*, **223**, 973.
Johnston, M., Bradt, H., Doxsey, R., Gursky, H., Schwartz, D., and Schwarz, J. 1978, *Ap. J.* (*Letters*), **223**, L71.
Johnston, M., *et al.* 1979, in preparation.
Johnston, M. D. 1978, Ph.D. dissertation, MIT.
Kaluzienski, L. J. 1977, Ph.D. dissertation, University of Maryland.
Katz, J. 1977, *Ap. J.*, **215**, 265.
Kylafis, N.D., and Lamb, D. G. 1978, *Ap. J.* (*Letters*), **228**, L105.
Li, F., Rappaport, S., and Epstein, A. 1978, *Nature*, **271**, 37.
Lucke, P. B., and Hodge, P. W. 1970, *A.J.*, **75**, 171.
Maraschui, L., Treves, A., and van den Heuvel, E. 1976, *Nature*, **259**, 292.
McCluskey, G. E., and Kondo, Y. 1971, *Ap. Space Sci.*, **10**, 464.
Rappaport, S., Buff, J., Clark, G., Lewin, W. H. G., Matilsky, T., and McClintock, J. 1976, *Ap. J.* (*Letters*), **206**, L139.
Rappaport, S., Clark, G. W., Cominsky, L., Joss, P. C., and Li, F. 1978, *Ap. J.* (*Letters*), **224**, L1.
Ricketts, M. J., Cooke, B. A., and Pye, J. P. 1978, *Bull. AAS*, **10**, 516.
Schrijver, J., Brinkman, A. C., Heise, J., den Boggende, A. J. F., Gronenschild, E. H. B. M., Mewe, R., Grindlay, J. E., and Parsignault, D. R. 1978, *Astr. Ap.*, **69**, L1.
Stier, M., and Liller, W. 1976, *Ap. J.*, **206**, 257.
White, N. E. 1978, *Nature*, **271**, 38.
White, N. E., and Carpenter, G. F. 1978, *M.N.R.A.S.*, **183**, 11P.

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