THE ASTROPHYSICAL JOURNAL, 228:L19–L22, 1979 February 15

DETECTION OF SOFT X-RAY EMISSION FROM SMC X-1

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Received 1978 September 25; accepted 1978 November 9

ABSTRACT

An intense and variable flux of soft X-rays extending up to ~1 keV was observed by the Wisconsin experiment on *OSO 8* on 1977 May 2–4 from the direction of SMC X-1. The emission ended abruptly when SMC X-1 went into eclipse at JD 2,443,268.4. The average pre-eclipse flux incident on the detector was 6.2×10^{-11} ergs cm^{-2} s^{-1} in the energy range 0.18–0.28 keV. Assuming a distance of 68 kpc and correcting for attenuation by the 3.4×10^{20} H atoms cm^{-2} of intervening galactic gas only, we derive a source luminosity of 5×10^{38} ergs s^{-1} in 0.18–0.28 keV, a factor of ~40 greater than the observed coincident 0.8–3 keV luminosity. Allowing for the apparent softness of the spectrum, we calculate a luminosity of $\sim 3 \times 10^{39}$ ergs s^{-1} for the full soft X-ray range of 0.15–0.8 keV, based on a best-fit spectral model for this 2 day flaring period. An earlier *OSO 8* observation of SMC X-1 at the same phase (0.4–0.9) in its binary orbit, also at a time when the hard X-ray source was in a low state, yielded an 0.18–0.28 keV upper limit of $\sim 3.3 \times 10^{-12}$ ergs cm^{-2} s^{-1}.

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

I. INTRODUCTION

The X-ray binary pulsar SMC X-1 (4U 0115−73) in the Small Magellanic Cloud is, when at its brightest, one of the most luminous stellar X-ray sources known. It is also known to be one of the most variable with estimates of the average 2–10 keV flux ranging from $< 5 \times 10^{-11}$ ergs cm^{-2} s^{-1} (Forman *et al.* 1978; Cooke *et al.* 1978; Markert *et al.* 1979) to 1.7×10^{-9} ergs cm^{-2} s^{-1} (Price *et al.* 1971). The source is characterized by extended low intensity periods which are apparently unrelated to the 3.89 day binary period (Schreier *et al.* 1972) and by a rather flat X-ray spectrum, photon index 0.8 to 1.15 (Schreier *et al.* 1972; Lucke *et al.* 1976; Clark *et al.* 1978). Both of these characteristics are similar to the galactic X-ray binary Her X-1. It has been suggested (Lucke *et al.* 1976) that SMC X-1 may emit a strong soft X-ray flux similar to Her X-1, which releases more energy below 1 keV than from 2 to 6 keV (Catura and Acton 1975; Bunner 1978). However, previous observations of SMC X-1 with sensitivity below 1 keV have not seen an additional soft component, setting upper limits to the flux from SMC X-1 at $\frac{1}{4}$ keV of typically 0.1 photons cm^{-2} s^{-1} keV^{-1} (4×10^{-11} ergs cm^{-2} s^{-1} keV^{-1}) (McCammon 1971, at binary phase 0.39; Lucke *et al.* 1976, at binary phase 0.83 and at binary phase 0.88).

In this *Letter* we report the first observation of $\frac{1}{4}$ keV X-rays from SMC X-1, and in fact the first observation of $\frac{1}{4}$ keV X-rays from an extragalactic stellar source.

II. OBSERVATIONS

SMC X-1 was observed on two separate occasions, in 1975 October and 1977 May, by the Wisconsin soft X-ray experiment on *OSO 8*, as part of a study of the diffuse background in the vicinity of the Small Magellanic Cloud (see Bunner, Sanders, and Nousek 1979). SMC X-1 was within 2° of the center of the experiment's 3° field of view from 1975 October 27.3 to October 30.3 (binary phase 0.17–0.96), and from 1977 May 2.3 to May 7.7 (1.4 binary cycles beginning at phase 0.25 and ending at 0.65).

Details of the Wisconsin *OSO 8* instrument are provided by Borken and Iwan (1977) and Bunner (1978). The observations were made with the forward axis low-energy detectors which are sensitive from 0.15 to 6 keV. The methane-filled soft X-ray proportional counter employs a Kimfol (polycarbonate) window. The experiment integration time is 20.5 s, too long to study the 0.716 s SMC X-1 pulsations (Lucke *et al.* 1976).

During both of the observation periods discussed here, the hard X-ray source SMC X-1 was in a "low" intensity state (1.5–6 keV flux $\leq 6 \times 10^{-11}$ ergs cm^{-2} s^{-1} and $\leq 3 \times 10^{-11}$ ergs cm^{-2} s^{-1} for the 1975 and 1977 observations, respectively). However, a strong and variable source of $E < 1.5$ keV X-rays was detected between 1977 May 2.0 and May 4.9. The former time corresponds to acquisition of SMC X-1 by the slow-scanning field of view. The latter time corresponds closely to the predicted time for entrance into an SMC X-1 eclipse: using the revised binary period of 3.89229 ± 0.00004 days (Davison 1977) and the center of eclipse time from *SAS 3* at JD $2,442,836.69 \pm 0.02$ (Primini *et al.* 1976), the best prediction for center of eclipse during our 1977 May observations is JD $2,443,268.734 \pm 0.024$ = 1977 May 5.234. Taking the eclipse duration of $0^{\mathrm{d}}610 \pm 0^{\mathrm{d}}019$ reported by Primini *et al.* (1976), the predicted eclipse immersion time is 1977 May 4.93 ± 0.03. The coincidence of the cessation of the observed soft X-ray flare with this prediction of SMC X-1 eclipse immersion we take as strong evidence that the SMC X-1 system is responsible for the emission. No statistically significant emission is seen from the source on exit from the eclipse, predicted at 1977

May 5.54 ± 0.03, although SMC X-1 was still within 0°.2 of the center of field of view at this time.

Figures 1 and 2 show the X-ray count rates for this period for 3 pulse-height bands corresponding to 0.15–0.28 keV, 0.4–0.84 keV, and 0.84–1.6 keV. Figure 1 shows the raw total count rates with only non–X-ray

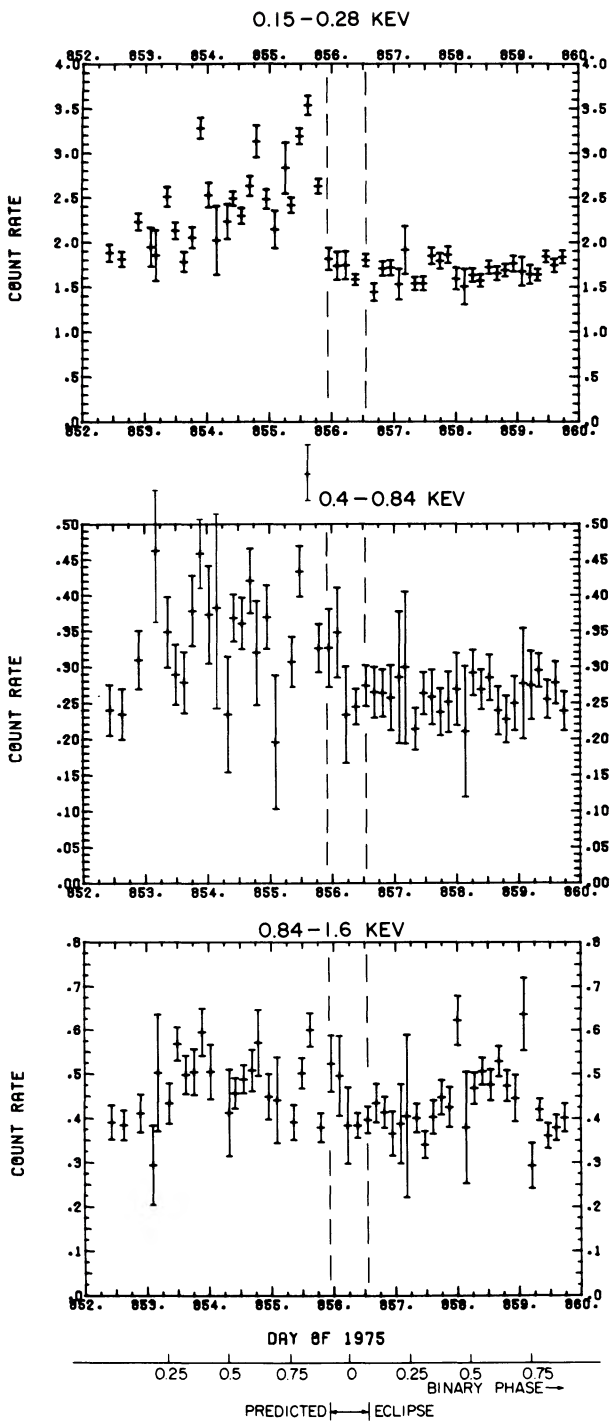

FIG. 1.—The raw *OSO 8* counting rates in counts s^{-1} (corrected only for non–X-ray background) in three energy bands for the period 1977 May 1.0 (=1975 day number 852.0) to 1977 May 9.0 (=1975 day number 860.0). Data are plotted in 3 hour time bins. Closest approach of the center of the 3° field of view to SMC X-1 is at day 855.3, although this source is within 0°.8 of the instrument axis from day 853.7 to 858.3. Closest approach to SMC X-2 is at day 853.4; closest approach to SMC X-3 is at day 858.7. Predicted center of SMC X-1 eclipse (binary phase 0) at JD 2,443,268.73 falls at 1975 day number 856.23.

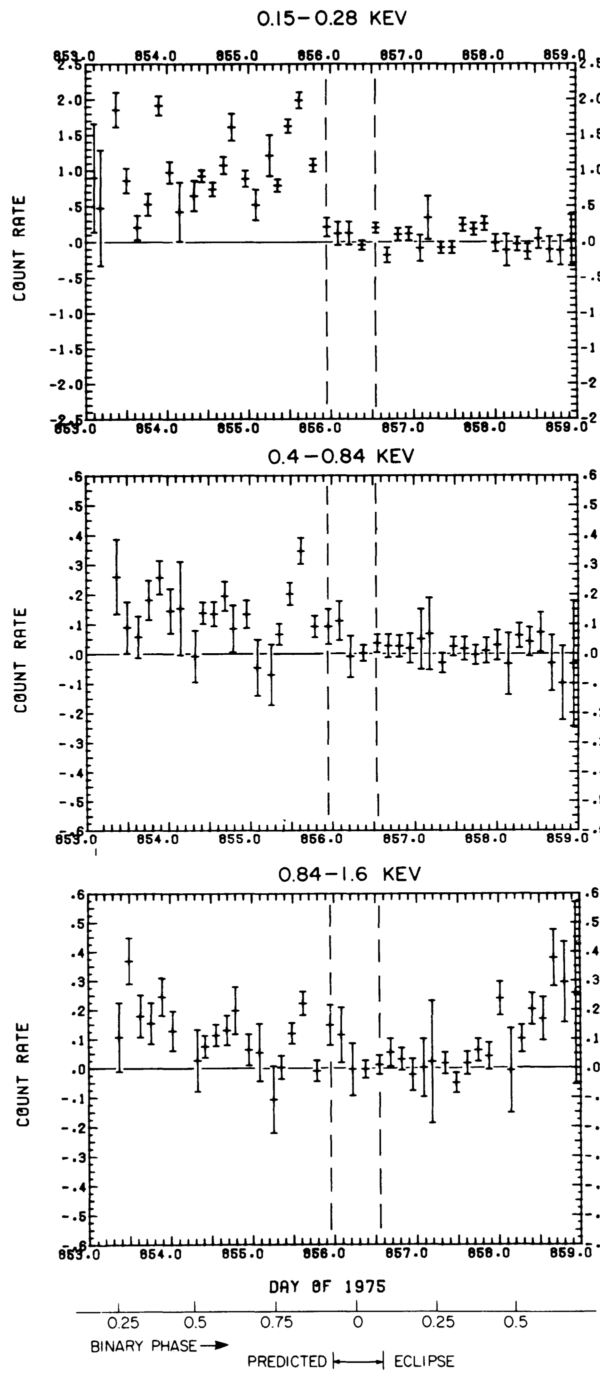

FIG. 2.—The net source light curve. The data of Fig. 1 are here corrected for diffuse background and for off-axis response. *Vertical dashed lines*, predicted entrance and exit from the SMC X-1 hard X-ray eclipse of 1977 May 5, using ephemeris data from Davison (1977) and Primini *et al.* (1976).

background subtracted. Figure 2 shows the net source intensity, corrected for diffuse background and for collimator response, assuming the source to be at the position of SMC X-1/Sk 160. Several features are noteworthy: a high degree of variability is seen in all three energy bands, with factor ~2 changes on time scales of 3 hours or less. A hint of a ~0.86 day periodicity appears in the variations. In the lowest-energy band (which corresponds principally to 0.18 keV $< E <$ 0.28 keV photons) the entrance into eclipse appears to begin ~$0^d.24$ prior to the predicted time of immersion and to proceed with a fall time of ~$0^d.11$. The intensity falloff need not be associated with the onset of the eclipse itself, since similar variations are seen during the preceding 2.4 days. If, in fact, the soft X-ray falloff between May 4.65 (1975 day 855.65) and May 4.9 (1975 day 855.9) is associated with the immersion into eclipse, it is clearly a slower transition than the abrupt ($\tau \leq 0^d.05$) transition seen in the hard X-ray data of Schreier *et al.* (1972) and could suggest an extended (~6×10^{11} cm) scattering cloud for the source of the soft X-rays, as proposed in accretion disk models, such as that of Basko and Sunyaev (1976) or van Paradijs and Zuiderwijk (1977), for example. Since a neutron star of radius r = 10 km cannot emit more than the blackbody limit of $4\pi\sigma_B r^2 T^4 = 7 \times 10^{32}\ T_6^4$ ergs s^{-1}, this geometry could alleviate the difficulty of having too high a soft X-ray luminosity from too small a source. Such an extended source model could quickly be discarded if the 0.716 s pulsations are found to persist down to $\frac{1}{4}$ keV.

Following emersion from eclipse predicted at May 5.54 ± 0.04 (day 856.54 ± 0.04) no trace of the 0.15–0.84 keV emission reappears, although the 0.84–1.6 keV emission appears to return following May 7.0 (day 858.0) at phase 0.45. In deriving Figure 2, we have interpreted this later 0.84–1.6 keV flux as also due to SMC X-1. It is also possible that this increase is due to SMC X-3 (Clark *et al.* 1978) which in fact is close to the center of the field of view at May 7.7 (day 858.7).

III. SPECTRUM AND LUMINOSITY

The spectrum appears to be variable during the flaring state of May 2.0 to May 4.9, the high intensity points generally corresponding to a softer spectrum. Lumping together the data from May 2.9 to May 4.9, and following the usual procedure of finding a mathematical model source spectrum which accurately fits the observed pulse-height distribution, we can derive estimates of the average source intensity in various energy ranges. Single-component models (power law, bremsstrahlung, blackbody, and other simple physical models) provide unacceptable fits to the data. Moreover, the goodness of fit rapidly worsens if any low-energy absorption is included in the model. A good fit to the data ($\chi^2 = 2.4$ for 4 degrees of freedom) is provided by the two-component model

$$\frac{dn}{dE} = \{6.2 \times 10^9 E^2[\exp(E/kT) - 1]^{-1} + 0.9/E \exp(-E/0.27)\} \exp(-3.4 \times 10^{20}\sigma) \text{ photons cm}^{-2}\text{ s}^{-1}\text{ keV}^{-1},$$

where E is in keV, $T = 0.15 \times 10^6$ K, and σ is the energy-dependent interstellar gas cross section in cm^2 per hydrogen atom (Brown and Gould 1970). This model does not necessarily have physical significance, but does reproduce well the observed count rate in each energy bin of the experiment. If a power law of number index 1.2 is added to the model (as in Fig. 3), the best-fit amplitude for this term is 0.0005 ± 0.0004 $E^{-1.2}$ photons cm^{-2} s^{-1} keV^{-1} and the χ^2 is not significantly improved (as contrasted, for example, with the 0.04 $E^{-1.2}$ spectrum found by Ulmer *et al.* [1973] when the hard X-ray source SMC X-1 was evidently in a high intensity state). The corresponding intensity incident on the detectors is 6.2×10^{-11} ergs cm^{-2} s^{-1} in the energy range 0.18–0.28 keV, 3.3×10^{-11} ergs cm^{-2} s^{-1} in 0.5–0.8 keV, and 2.1×10^{-11} ergs cm^{-2} s^{-1} in 0.8–3 keV. For a wide variety of trial spectral models, no additional absorption is required beyond the 3.4×10^{20} H cm^{-2} of known intervening galactic gas (McCammon *et al.* 1976).[1] The column density of high-velocity H I associated with the SMC along the same line of sight ($01^h15^m.6$, $-73^\circ.6$) is ~45×10^{20} H cm^{-2} (Hindman

[1] The range of acceptable ($\chi^2 < 8$ for 4 degrees of freedom) absorption column density in the above model is $0 \leq N_H \leq 6 \times 10^{20}$ H cm^{-2}. If a steep power law or a low-temperature bremsstrahlung continuum is used to model the very soft component required by the observed pulse-height distribution, the fit is less satisfactory and still requires $N_H < 5 \times 10^{20}$ H cm^{-2} for $\chi^2 < 10$.

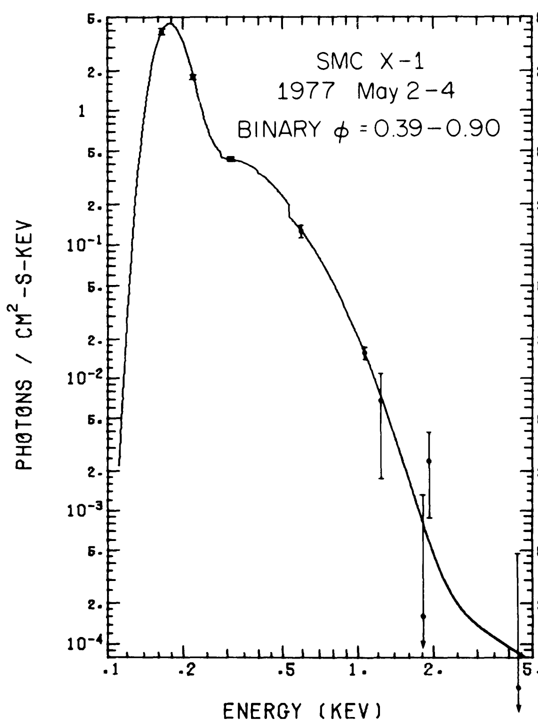

FIG. 3.—The derived (source−diffuse background) spectral distribution incident on the detectors. Shown for comparison is a mathematical model (see text) which is a good empirical fit to the data. Errors shown are statistical only. An X-ray absorption measure of 3.4×10^{20} H cm^{-2} is allowed by the data but, for a variety of simple physical models tested, much higher values would be difficult to accommodate.

1967). Since the effective cross section per H atom at 250 eV is essentially unaffected by the heavy-element depletions discussed in Bunner *et al.*, the data are suggestive that SMC X-1 lies on the near side of the SMC neutral gas. After correction only for the expected attenuation by the galactic gas and assuming a distance of 68 kpc, the corresponding source luminosity in the band 0.18 to 0.28 keV is 5×10^{38} ergs s^{-1}, a factor of $\sim$40 above the observed coincident 0.8–3 keV luminosity. The determination of the luminosity over the full soft X-ray range of 0.15–0.8 keV is more model-dependent, since the inferred spectrum is very soft and the detectors have little sensitivity below 0.18 keV. Again correcting only for the expected attenuation by galactic gas (3.4×10^{20} H cm^{-2}), we derive an average soft X-ray luminosity of $\sim 3 \times 10^{39}$ ergs s^{-1} over this 2 day flaring period in 1977, with the peak luminosity reaching twice the value.

For the 1975 October *OSO 8* observations, no soft X-ray flux attributable to a point source was seen, although a hard X-ray source is marginally detected. The corresponding derived flux and upper limits for the interval 1975 October 27.3–29.8 when SMC X-1 was within $\sim 1\overset{\circ}{.}5$ of the center of the field of view, at binary phase 0.17–0.81, are $< 3.3 \times 10^{-12}$ ergs cm^{-2} s^{-1} in the 0.18–0.28 keV band, $< 1.5 \times 10^{-11}$ ergs cm^{-2} s^{-1} in the 0.5–0.8 keV band, and 2.4 (+1.3, −0.5) $\times 10^{-11}$ ergs cm^{-2} s^{-1} in the 0.8–3 keV band. We cannot rule out the possibility that SMC X-2 and SMC X-3 (Clark *et al.* 1978) are contributing somewhat to the measured 1975 0.8–3 keV flux, as both sources are within the field of view during parts of this time interval. No change in the measured rates is evident at the predicted time of SMC X-1 immersion into eclipse at 1975 October 30.22 = JD 2,442,715.72 ± 0.04. Table 1 provides 3 σ upper limits for the flux from point sources at the positions of SMC X-2 and SMC X-3, for both the 1975 and 1977 observation periods.

TABLE 1

0.8–3 keV Flux Upper Limits (ergs cm^{-2} s^{-1})

	1975 Oct.	1977 May
SMC X-2	4.5×10^{-11}	5.8×10^{-11}
SMC X-3	4.8×10^{-11}	3.1×10^{-11}

IV. SUMMARY

The variable soft X-ray source observed while the *OSO 8* field of view was centered on SMC X-1 in 1977 May is identified with the hard X-ray source SMC X-1 by the rather abrupt ending to the emission (fall time $\sim$2.5 hours), ending at the time SMC X-1 is expected to enter eclipse. The soft X-ray intensity on emergence from eclipse 15 hours later is reduced by a factor ≥ 20 from the peak intensity prior to eclipse. This asymmetry may reflect a geometry in which the soft X-ray source trails the compact star as in an accretion stream model. An average intensity at $\frac{1}{4}$ keV of $\sim$1 photon cm^{-2} s^{-1} keV^{-1} was observed. Correcting only for absorption by the intervening galactic gas, the derived soft X-ray luminosity in the 0.15–0.8 keV range is as high as $\sim 6 \times 10^{39}$ ergs s^{-1} during this pre-eclipse flare, an order of magnitude greater than the usual reported high state 2–10 keV intensity for SMC X-1 (Forman *et al.* 1978).

This research was supported by the National Aeronautics and Space Administration under contract NAS5-22410. We acknowledge the helpful comments of William Kraushaar, Don Cox, and DeAnn Iwan. The contributions of Rick Borken were fundamental to the data processing. We thank Joe Rueden for computer programming assistance.

REFERENCES

Basko, M. M., and Sunyaev, R. A. 1976, *M.N.R.A.S*, **175**, 395.
Borken, R. J., and Iwan, D. C. 1977, *Ap. J.*, **218**, 511.
Brown, R. L., and Gould, R. J. 1970, *Phys. Rev. D*, **1**, 2252.
Bunner, A. N. 1978, *Ap. J.*, **220**, 261.
Bunner, A. N., Sanders, W. T., and Nousek, J. A. 1979, *Ap. J. (Letters)*, **228**, this issue.
Catura, R. C., and Acton, L. W. 1975, *Ap. J. (Letters)*, **202**, L5.
Clark, G., Doxsey, R., Li, F., Jernigan, J. G., and van Paradijs, J. 1978, *Ap. J. (Letters)*, **221**, L37.
Cooke, B. A., *et al.* 1978, *M.N.R.A.S.*, **182**, 489.
Davison, P. J. N. 1977, *M.N.R.A.S.*, **179**, 15p.
Forman, W., Jones, C., Cominsky, L., Julien, P., Murray, S., Peters, G., Tananbaum, H., and Giacconi, R. 1978, *Ap. J. Suppl.*, **38**, 357.
Hindman, J. V. 1967, *Australian J. Phys.*, **20**, 147.
Lucke, R., Yentis, D., Friedman, H., Fritz, G., and Shulman, S. 1976, *Ap. J. (Letters)*, **206**, L25.
Markert, T. H., *et al.* 1979, *Ap. J. Suppl.*, **39**, in press.
McCammon, D. 1971, Ph.D. thesis, University of Wisconsin–Madison.
McCammon, D., Meyer, S. S., Sanders, W. T., and Williamson, F. O. 1976, *Ap. J.*, **209**, 46.
Price, R. E., Groves, D. J., Rodrigues, R. M., Seward, F., Swift, C. D., and Toor, A. 1971, *Ap. J. (Letters)*, **168**, L7.
Primini, F., Rappaport, S., Joss, P.C., Clark, G. W., Lewin, W., Li, F., Mayer, W., and McClintock, J. 1976, *Ap. J. (Letters)*, **210**, L71.
Schreier, E., Giacconi, R., Gursky, H., Kellogg, E., and Tananbaum, H. 1972, *Ap. J. (Letters)*, **178**, L71.
Ulmer, M. P., Baity, W. A., Wheaton, W. A., and Peterson, L. E. 1973, *Nature Phys. Sci.*, **242**, 121.
van Paradijs, J., and Zuiderwijk, E. 1977, *Astr. Ap.*, **61**, L19.

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